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Groundwater Management: Efficiency and Equity Considerations

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Abstract

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Groundwater has the characteristics of commonly owned property, and its use is likely to be inefficient in the absence of regulation. Several management tools can be used to regulate groundwater withdrawals, with no one tool dominating the others in terms of efficiency of water use. However, the welfare distributional effects of various management schemes on individual users who vary in their derived demands for groundwater might be quite substantial, and different users may find considerably different schemes attractive.

The equity problems associated with the division of management benefits may dominate the decisions about support of or opposition to groundwater management, and hence they must be undertaken with considerable care and resolved by consensus among users. Although the negotiations are expected to be extensive and complicated, there is a substantial basis for agreement because all users stand to gain; the question is, who will gain the most?

Introduction

As a common property resource, groundwater use is likely to be inefficient in the absence of regulation (Milliman, 1956; Hirshleifer et al., 1960; Gisser and Sanchez, 1980). Under competition (assuming a large number of pumpers relative to the size of the aquifer), each user perceives that his water withdrawals in the current period will have a negligible effect on the future groundwater tables, and hence his decision-making is based solely on the consideration of his immediate profits. In other words, a competitive user has no incentive to account for the exernal diseconomies he imposes on other users (the "If I do not pump it, my neighbor will" attitude). The fact that water use is not efficient means that there is some way to improve the welfare of one group of pumpers without reducing that of another group.

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One can think of several management schemes which result in the same aggregate profits but have different impacts on wealth-distribution among individual users. A water-management scheme, even one that promotes efficiency, is expected to be resisted by the users who will suffer distributional losses, no matter how large the improvement in allocative efficiency. As a result, the issue of efficient resource allocation cannot be isolated from the distributional issue. In other words, "economic theory that puts efficiency above the distributional requirements ... is doomed to be ignored by policy makers" (Nunn, 1985), or, "water equity and distributional considerations are at least as important as the efficiency objective" (Scherer, 1977).

Economic aspects of groundwater usage have been discussed extensively in the literature (e.g., Milliman, 1956; Hirshleifer et al., 1960; Brown and McGuire, 1967; Burt, 1970). However, evidence on the benefits to be gained from management is relatively limited. Previous studies investigated benefits to users *in aggregate* (e.g., Howitt, 1979; Feinerman and Knapp, 1983) and ignored equity and distributional effects of different management schemes on individual pumpers, who differ in their demands for groundwater and do not share the benefits equally. However, preliminary results were reported in Knapp and Vaux (1982). Assuming different groups of pumpers and several quota-allocation strategies, they presented an empirical example which demonstrates that some users may suffer substantial losses from groundwater management even though the group as a whole benefits. However, they did not explicitly discuss efficiency, equity and administrative aspects of the proposed strategies nor investigate options for improving the benefits distribution. These are issues whose solution is essential for achieving a mutually agreed-upon regulation among the basin's users.

In this paper, the welfare effects of various groundwater management policies on individual users who differ in their derived demands for groundwater are investigated. A large number of farmers, each owning land overlying a single-cell aquifer, are considered. Formulas aimed at comparing the present value of annual net benefits, under no-management (competition), and optimal control, are developed using dynamic programming and applied to a situation in Kern County (KC), California. Then options of utilizing taxes and quotas to regulate groundwater demands are presented and some of their welfare, equity and administrative aspects are analyzed and compared. Although various management tools can in concept induce efficiency of water use, and yield the same management benefits in aggregate, the analysis demonstrates that individual users may find considerably different tools attractive and suggests that, without extensive negotiations among users, no-management is likely to be instituted.

1. Frame of analysis

Consider a large number of farmers, each owning land overlying a single-cell aquifer of groundwater. The farmers rely on both surface and groundwater for irrigation supplies. It is assumed that surface supplies are constant[1], are uncontrolled by the farmers, and are used in preference to pumping groundwater (being cheaper and/or of better quality) at predetermined levels.

Total groundwater withdrawals at year t are denoted by W_t, pumping lifts by h_t, and average annual surface inflows (e.g., rivers, artificial water projects, minor streams, precipitation) to the land overlying the aquifer by I. Let γ be the fraction of surface inflows (I) diverted to irrigation ($0<\gamma<1$), and θ be the fraction of applied irrigation water returning to the groundwater table ($0<\theta<1$). Total applied irrigation water at year t is therefore W_t (groundwater) $+\gamma I$ (surface water), and of this $\theta(W_t+\gamma I)$ returns to the aquifer from deep percolation (indirect recharge). Direct recharge to the aquifer from canal losses, deep percolation of natural stream flows and artificial recharge programs is given by $(1-\gamma)I$. Average annual underground recharge to the aquifer net of underground outflows is denoted $\bar{R}$.

The farmers vary in their derived demand functions for groundwater (due to variation in acreage, soil types, rights to surface water, climate and agricultural expertise), but have identical pumping-cost functions (all of them are pumping from the same lift using the same technology).[2] The annual net benefits (in US$) to farmer i at year t of water withdrawn from the groundwater basin, W_{ti} (acre ft), from a lift of height h_t (ft) are given by:

$$\pi_t^i = a_i W_{ti} - \tfrac{1}{2} b_i W_{ti}^2 - e h_t W_{ti} \tag{1}$$

where a_i, b_i are the intercept and the slope for the groundwater demand curve of the ith farmer[3], respectively; and e pumping costs per acre ft per ft of lift. The state variable's (h_t) equation of motion is:

$$h_{t+1} = h_t - \frac{R + (\theta - 1) W_t}{As} \tag{2}$$

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[1] It is acknowledged that surface water supplies are typically variable and groundwater is used to offset fluctuations in surface water deliveries. However, it is usually true that users contract for surface water diversions and thus, do not have the short-term flexibility they have with groundwater pumping from their own wells. Assuming away surface water fluctuations simplifies the analysis substaintially and focuses the study on the policy issues which are associated with the management of a common property groundwater resource.

[2] It should be noted that the derived demand for water (i.e., the value of marginal product of water) is a function of output prices, inputs other than water, production technology, etc., but itself does not depend on the (current and future) pumping lift and costs and is not influenced by the external diseconomies which are associated with competitive water withdrawal.

[3] Accounting for the (constant) surface water supplies, the intercept and the slope of the ith farmer's groundwater demand curve are $a_i = a_i' - b_i \gamma I$ and $b_i = b_i'$ respectively; where a_i' and b_i' are the intercept and the slope, respectively, of the farmer's water (surface water and groundwater) demand curve.

ft, foot = 0.3048 m.
acre ≈ 0.404686 ha ≈ 4047 m^2.
acre ft, acre-foot ≈ 123.35 ha mm ≈ 1234 m^3.

where $R=\bar{R}+(1+\gamma(\theta-1))I$, the recharge to the aquifer from all sources except deep percolation of applied groundwater; A the area of the aquifer (acre), s the specific yield of the aquifer, and $W_t=\sum_i W_{ti}$.

Suppose now a hypothetical groundwater management agency (GMA) wishes to maximize the aggregate present value of the farmer's net profits. Assuming an infinite time horizon, and following the theory of dynamic programming (e.g., Bertsekas, 1976), the maximization problem is formulated as follows:

$$J(h_t)=\max_{W_{ti}}\ [\sum_i \pi_t^i+\alpha J(h_{t+1})] \tag{3}$$

where $\alpha=1/(1+r)$, and r is the annual interest rate.

The derivations of the first-order necessary conditions of (3) and its implied (optimal control) steady-state (SS) pumping level (W_s), pumping lift (h_s) and marginal user cost ($\mathrm{MUC_s}$) are left to the Appendix. The SS pumping level (W_s^*) and lift (h_s^*) under competition and the SS and the actual benefits from groundwater management of the ith farmer, $(\mathrm{BGWM})_\mathrm{s}^i$ and $(\mathrm{BGWM})^i$, respectively, are also derived in the Appendix.

Based on the Appendix's derivations, several observations and conclusions should be made:

(1) The SS lift under optimal control is lower than the one under competition (i.e., $h_\mathrm{s}<h_\mathrm{s}^*$).

(2) The total SS pumping level W_s is independent of the particular management scheme being assumed. This, coupled with the fact that under both management schemes W_s is allocated among the farmers such that the values of their marginal products are equal, yields $W_{\mathrm{s}i}=W_{\mathrm{s}i}^*$ for every i, where $W_{\mathrm{s}i}$ and $W_{\mathrm{s}i}^*$ are, respectively, the SS pumping levels of the ith farmer under optimal control, and under competition.

(3) Marginal user cost is the reduction in discounted future net benefits from a withdrawal of one additional unit in the current period. In the SS, future pumping is just equal to current pumping W_s. The last unit pumped in the current period will increase the future lift and pumping costs by $(1-\theta)/As$ (see equation 2) and $eW_\mathrm{s}(1-\theta)/As$, respectively. $\mathrm{MUC_s}$, which is given by equation (A4), is exactly the discounted value of the additional pumping costs.

(4) While calculating $(\mathrm{BGWM})_\mathrm{s}^i$ (equation A7) it was implicitly assumed that both management schemes (optimal control, and competition) have begun at the same time in different pumping lifts. Clearly, this assumption is not legitimate and it was relaxed while $(\mathrm{BGWM})^i$ (equation A8) was derived. For the sake of simplicity, it was assumed that the current ($t=1$) pumping lift is identical to the SS pumping lift under optimal control, h_s. If optimal control management is initiated at this time, the left will stay unchanged. Under competition the lift, h_t^*, will increase over time and will ultimately converge to h_s^*. Initially, the annual net benefits under competition, π_t^{*i}, are greater than the annual net benefits under optimal control, π_s^i; however, under competition,

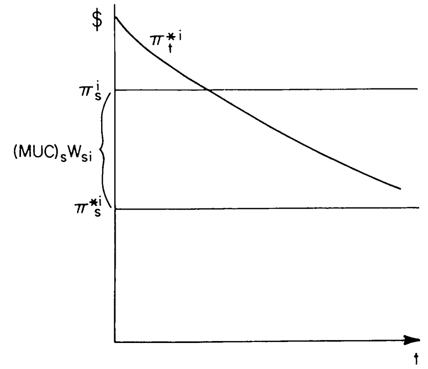

Fig. 1. Annual net benefits from groundwater pumping under competition and regulation, assuming $h_1 = h_s$.

lifts and marginal pumping costs will increase over time. As a result, optimal pumping levels and annual net benefits will decrease, and will ultimately converge to their SS values W_{si} and π^{*i}_s (Fig. 1).

Hence it is obvious that benefits from groundwater management, which neglects the transition from h^*_s to h_s (equation A7), overestimates the actual benefits which might be substantially smaller (i.e., $(\text{BGWM})^i_s > (\text{BGWM})^i$).

(5) Clearly, identical benefits should not be expected among users who differ in their derived demand functions. Furthermore, as demonstrated by Knapp and Vaux (1982), it is not obvious a priori that the benefits will not be negative for some of the farmers.

2. Empirical specification

The conceptual model presented in the previous section and in the Appendix is applied to Kern County in California, which represents a critical area for groundwater management since there is a heavy reliance on groundwater to meet agricultural water demands.

Area of the aquifer (A) and an average specific yield (s) were calculated from a publication of the California Department of Water Resources (DWR, 1977); an estimate of the deep percolation coefficient (θ) was obtained from the same source. Average annual surface inflow (I) was calculated from historical data in DWR (1977) and Kern County Water Agency (KCWA, 1979). The value of average annual groundwater recharge $\bar{R}$ was obtained from the latter source. An estimate of the fraction of surface inflow diverted to irrigation (γ) was calculated from data in KCWA (1980) and previous issues. Energy costs of pumping (e) were calculated assuming 1.024 kWh per acre ft per ft of lift (KCWA, 1979), an average pumping plant efficiency of 60% (DWR, 1981) and electricity prices of \$0.05 per kWh (Christensen et al., 1982). The calculated parameter values are summarized in Table 1.

To the best of my knowledge, there is no actual detailed water demand study in Kern County which enables one to accurately differentiate the KC member farmers according to their derived demand for irrigation water. However, Brown and McGuire (1967) presented rough estimates of linear water demand curves for several districts in KC. Based on their data (which were adjusted for inflation) and for illustrative purposes, four groups of pumpers, each consisting of identical farms, are distinguished in the present paper (from now on, the index i stands for group i). The data used to specify the groups are presented in Table 2.

By substituting the (hydrologic ane economic) parameter values in the model's equations, and assuming a real interest rate of 4%, the SS lift under optimal control (assumed to be the initial lift) and the SS lift under competition are 405.1 ($\approx$123.5 m) and 577.2 ft ($\approx$175.9 m), respectively. The marginal user costs and years to the SS under competition are \$15.49 per acre ft (\$125.60 per ha m) and 80 years (the time given is actually years to the neighborhood (5%)

TABLE 1

Hydrological parameters and energy costs

Parameter	Description	Value	
A	Aquifer area	1 290 000 acres	522 000 ha
s	Specific yield	0.10	
$\bar{R}$	Average annual groundwater recharge	52 000 acre ft/year	6 400 ha m/year
I	Average annual surface inflow	1 900 000 acre ft/year	234 000 ha m/year
Y	Fraction of surface inflow diverted to irrigation	0.7	
θ	Deep percolation coefficient	0.2	
e	Energy costs	\$0.09 per acre ft/year	\$0.73 per ha m/year

TABLE 2

Assumed groundwater demand parameters and acreage by group

Group No.	Demand Curve			
	Intercept	Slope	Area	
			(acre)	(ha)
1	76.6	0.0000408	461 840	186 900
2	74.8	0.000168	200 800	81 260
3	73.8	0.000127	200 800	81 260
4	84.6	0.000165	140 560	56 880

TABLE 3

Benefits ($ per area) under competition (B_i^*) and optimal control (B_i) and actual $(\text{BGWM})^i$ and SS $(\text{BGWM})_s^i$ benefits from groundwater management

Group	B_i^*		B_i		$(\text{BGWM})^i$	$(\text{BGWM})_s^i$
	(acre^{-1})	(ha^{-1})	(acre^{-1})	(ha^{-1})		
1	787.3	1945.5	909.5	2247.4	122.2	506.5
2	395.4	977.0	455.7	1126.0	60.3	262.3
3	491.7	1215.0	565.7	1397.9	74.0	331.8
4	969.1	2394.7	1119.5	2766.3	150.4	545.1

of the steady state), respectively. Present values of net benefit under optimal control (B_i) and competition (B_i^*), and actual $(\text{BGWM})^i$ and SS $(\text{BGWM})_s^i$ benefits from groundwater management, all computed on a per-area basis, are presented in Table 3. Note that SS benefits from groundwater management are about 4 times as large as the actual benefits.

Up to this point, benefits from groundwater management have been discussed with no mention of any specific regulation scheme. Various means of regulating groundwater withdrawals can be used by the GMA to induce efficient use but their impacts on the welfare of groundwater users can be quite different as discussed and demonstrated in the following section.

3. Policy issues

Economists usually favor systems of taxes or market-like mechanisms as the most desirable and efficient means of managing demands. Almost any mechanism has the potential for considerable redistribution of wealth among the basin's farmers. The fact that many basins in California are not managed, even though it is generally believed that management would be beneficial, suggests that redistribution and equity issues may dominate the decisions about support of or opposition to groundwater management (Phelps et al., 1978).

In the following, the options of utilizing taxes and quotas to regulate groundwater demands are presented and some of their welfare, equity and administrative aspects are discussed.

3.1 Pump taxes

Imposition of a constant pump tax equal to $(\text{MUC})_s$ ($ per acre ft) will induce users to cut back withdrawals to the optimal levels W_{si}'s. If the tax payments collected by the GMA are not rebated, this optimal Pigouvian tax will result in a loss in welfare to each and every one of the resource users. This proposition is verified in the Appendix, equations (A7) and (A8): the annual pump tax payments by the ith group amount to W_{si} (MUC)$_s$ and its present value, (PVT)^i is:

$$(\text{PVT})^i = \frac{W_{si}\,(\text{MUC})_s}{r} = (\text{BGWM})^i_s > (\text{BGWM})^i \quad \text{for every } i \tag{4}$$

The calculated benefits under this management scheme are \$ − 384.3, − 202.0, − 253.9 and − 394.7 per acre (− 949.6, − 499.2, − 625.2 and − 975.3 per ha) for groups 1 to 4, respectively. These values suggest that the above-mentioned loss may be quite substantial. Partial graphical analysis presented in Milliman (1956), and empirical analysis presented in Knapp and Vaux (1982) and Feinerman and Knapp (1983), yielded the same conclusion. Similar results are obtained in Weitzman (1974) for static models of common-property resources.

The observation that optimal Pigouvian tax (Pigou, 1951), without rebate, will result in a loss in welfare to each user can be visualized with the aid of Fig. 2. D_i is the derived demand curve for groundwater of the ith farmer. $\text{MP}_1 = eh_s$ is the marginal pumping cost curve at $t = 1$, where the pumping lift is assumed to be identical to the SS lift under optimal control, h_s. $\text{MS} = \text{MP}_1 + (\text{MUC})_s$ is the marginal social cost curve at $t = 1$. If optimal control management is initiated at this time, the lift (h_s) and the quantity of water withdrawn by the ith farmer (W_{si}) will stay unchanged. Under optimal control the Pigouvian tax per acre ft is equal to (MUC)$_s$ and hence, the net annual benefits to the ith farmer, *without rebate*, is given by the area ABC between the marginal social cost curve, MS, and the marginal benefit (demand) curve, D_i.

Under competition, the initial lift, $h_1^* = h_s$, and the initial marginal pumping cost, MP$_1$, will increase over time and will ultimately converge to their SS levels, h_s^* and $\text{MP}_s = \text{MS}$, respectively. As a result, optimal pumping levels (W_{1i}^* at $t = 1$, W_{2i}^* at $t = 2$, etc.) and annual net benefits (the area AEF between MP$_1$

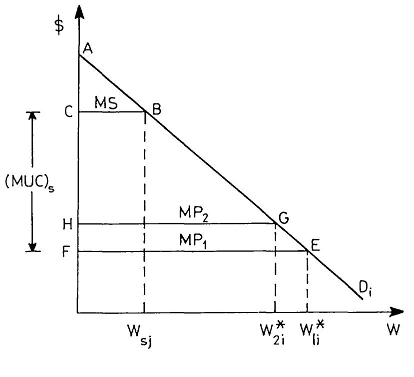

Fig. 2. Optimal Pigouvian tax and a loss in welfare.

and D_i at $t=1$, the area AGH between MP_2 and D_i at $t=2$, etc.) will decrease over time and will ultimately converge to their infinum SS values $W^*_{si} = W_{si}$ and the area ABC, respectively.

The important point is that during the transition from h^*_1 to h_s the annual net benefits under competition are always greater than the annual net benefits under optimal control (e.g., AEF > ABC, AGH > ABC), given that the Pigouvian tax payments are not rebated. In other words, regulating groundwater demands by imposition of an optimal Pigouvian tax (equal to $(\mathrm{MUC})_s$) which is not rebated will result in a loss in welfare to each user.

To conclude, equation (4), coupled with the fact that tax payments are imposed immediately upon management initiation while profits are realized only in the future, suggests substantial resistance of the basin's farmers to levying a constant pumping tax without rebate. If rebates are considered, it is essential that the scheme adopted will not affect marginal groundwater pumping decisions. Hence, they cannot be related to the optimal quantities pumped. Any other rebated mechanism should be easy to administer and should appeal on equity grounds. An equitable mechanism necessitates an equal per-unit rebate for an agreed-upon relevant variable (e.g., area farmed, premanagement groundwater withdrawals, premanagement revenues, etc.) and is probably a necessary condition for political acceptance of any rebate scheme. Besides the costs of its measurement, each candidate variable is expected to be judged by the resulting redistribution of management benefits associated with its choice. The inequality in the distribution of management benefits can be evaluated by comparing their absolute values (on a per-area base), $(\mathrm{BGWM})^i$, for the different groups; or if it is felt that management benefits should be in some proper relation to the users' respective wealth under no-management (competition), by comparing the proportional benefits $(\mathrm{BGWM})^i/B^*_i$.

The rate of benefits' inequality can be measured by Gini Coefficient (e.g., Deaton and Muellbauer, 1980):

$$\eta = \frac{1}{2N^2\bar{X}} \sum_{i=1}^{N} \sum_{j=1}^{N} |X_i - X_j|$$

where N is the number of the distinct groups, X_i is the absolute (or proportional) benefits of the ith group, and $\bar{X} = \sum_{i=1}^{N} X_i$. When there is a perfect equality, that is $X_i = \bar{X}$, $\eta = 0$, while with perfect inequality, $X_1 = N\bar{X}$, and $\eta = 1 - 1/N$. Although achieve of a low η is expected to be highly valued by the GMA, its significance to each of the users is limited. A private user will prefer a higher share in the total management benefits which is more closely associated with higher η than the opposite.

In Table 4, results associated with the two types of rebate schemes – a per-unit rebate for land use (scheme 1) and a per-unit rebate for premanagement groundwater withdrawals (scheme 2) – are presented. The impact of the different schemes on benefits redistribution suggests substantial disagreement

TABLE 4

Absolute and proportional benefits from groundwater management and Gini coefficient under two types of pump taxes rebate schemes

Per unit rebate for	Land use		Premanagement groundwater use	
	$(\text{BGWM})^i$	$(\text{BGWM})^i/B_i^*$	$(\text{BGWM})^i$	$(\text{BGWM})^i/B_i^*$
Group 1	43.0	0.0546	124.1	0.1576
Group 2	225.4	0.5701	69.2	0.1750
Group 3	173.5	0.3529	95.6	0.1944
Group 4	32.6	0.0336	100.7	0.1039
Gini coefficient η	0.3735	0.4717	0.1090	0.1145

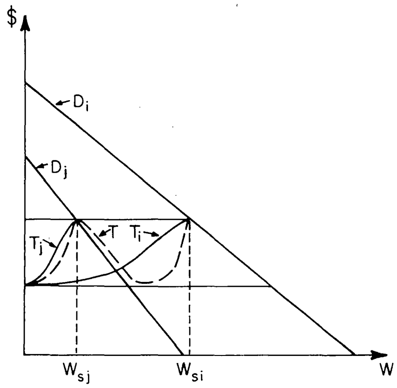

Fig. 3. Variable pump-taxes schemes.

and tedious negotiations[4] among users before adopting any specific scheme. Obviously, scheme 1 would be preferred by users of groups 2 and 3 while scheme 2 would be preferred by users of groups 1 and 4. Since the administrative costs associated with both schemes seem to be the same, adoption of scheme 2, which is associated with lower values of η, would be probably encouraged by the GMA.

Another way in which tax payments can be reduced is to allow pump taxes to vary, as a function of the quantity of water actually pumped. The idea of variable pump taxes was first proposed by Milliman (1956) and was also discussed in Wetzel (1978), Knapp and Vaux (1982) and Feinerman and Knapp (1983). In Fig. 3, D_i and D_j represent the derived demand functions of farmers

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[4] Agreement is reached through negotiation, bargaining and mutual persuasion which are usually costly in terms of time and human relationships, thus giving rise to bargaining cost. The cost is greater, the more diverse are user's interests and the less compromising are user's attitudes. Cultural factors are no doubt important determinants of the bargaining cost.

i and j, respectively. Water use can be restrained to the optimal levels, W_{si} and W_{sj}, by imposing variable pump taxes according to schedules such that the total marginal pumping costs to i and j have the shapes T_i and T_j, respectively. Obviously, variable pump taxes allow the farmers to capture most of the benefits from GWM without the need of rebate. However, there appears to be potential difficulties with such a scheme. A specific variable-tax scheme for each individual is very expensive and complicated to administer. Additionally, the schemes presented favor the ith farmers in comparison to the jth, and significant equity problems are expected to arise. An example of a unique variable-tax scheme, which is equally faced by all farmers (and hence might be regarded as an equitable policy mechanism) is presented by T in Fig. 3. Note that inducing the jth farmers to pump W_{sj} necessitates that the values of T (or at least a substantial portion of them) will be greater than those of D_j for $W > W_{sj}$. Such a 'crazy' tax scheme still seems to be administratively clumsy and associated with higher values of η.

3.2 Quotas

In contrast to the pump-taxes method, economically efficient quotas (property rights for pumping) assigned so that the marginal benefits of the last unit pumped are equal among all pumpers allows all the benefits from GWM to accrue to the individual farmers. On the other hand, such a scheme might result in substantially different quotas among farmers and, hence, major problems of equity are expected.

Perhaps an option that would strike one as equitable is the imposition of equal quotas per area (or per unit of some other agreed-upon variable). The result, however, will be inefficient because marginal benefits will not be equated (except by accident). Allowing trade in water rights will remove the inefficiency. At price of $(\text{MUC})_s$, quotas will be bought and sold until they end up in the optimal allocation. Under this policy, benefits will be transferred from purchasers to sellers of water rights. An alternative option is for the GMA to act as a mediator by buying and selling water rights at price of $(\text{MUC})_s$. Obviously, this option will also result in optimal pumping levels and the same redistribution of benefits as under the personal trading option. Under this option, however, the costly and sometimes unpleasant process of mutual trading among users, some of whom are probably close friends[5], will be avoided. Furthermore, in cases where this policy will result in substantial benefits transfer from purchasers to sellers, it can be used in conjunction with a retransferring mechanism aimed at increasing benefits equality (i.e., decreasing the value of η). It is essential that the adopted mechanism will appeal on equity grounds and will

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[5] Basic social psychological principles which help explain why it is difficult for friends to deal with each other in business transactions are presented in Jones (1972).

TABLE 5

Absolute and proportional benefits from groundwater management and Gini coefficient under five quota allocation strategies

Group	Strategy									
	1		2		3		4		5	
	$(\text{BGWM})^i$	$(\text{BGWM})^i/B_i^*$	$(\text{BGWM})^i$	$(\text{BGWM})^i/B_i^*$	$(\text{BGWM})^i$	$(\text{BGWM})^i/B_i^*$	$(\text{BGWM})^i$	$(\text{BGWM})^i/B_i^*$	$(\text{BGWM})^i$	$(\text{BGWM})^i/B_i^*$
1	122.2	0.1550	43.8	0.0556	125.0	0.1588	110.5	0.1404	116.9	0.1485
2	60.3	0.1525	226.2	0.5721	69.8	0.1765	126.2	0.3192	65.5	0.1660
3	74.0	0.1505	170.4	0.2455	92.3	0.1877	70.4	0.1432	86.8	0.1765
4	150.4	0.1552	33.4	0.0345	101.6	0.1048	100.1	0.1033	141.8	0.1463
Gini coefficient										
η	0.1957	0.0068	0.3720	0.4718	0.1125	0.1061	0.1092	0.2303	0.1575	0.0424

not affect marginal decisions associated with sale and purchase of water rights. Imposing an equal per-unit-sale tax for an agreed-upon relevant variable (rather than quantities sold) on sellers of water rights, and distributing the tax revenues as an equal per-unit subsidy among the purchasers of water rights, seems to be workable option.

For demonstration purposes, five allocation strategies are assumed. Under the first, quotas are assigned so that the marginal benefits of the last unit pumped are equal among all users. Under the second (third), equal quotas on a per-acre (per pre-management groundwater withdrawals) basis are assigned and water rights can be bought from and sold to the GMA at price of $\mathrm{MUC_s} = \$15.49$ per acre ft or \$125.58 per ha m. Under the fourth (fifth), the second (third) strategy combined with an imposition of \$4 per acre or \$9.9 per ha (\$0.20 per unit of pre-management withdrawals) sale tax on the sellers-groups 2 and 3 (groups 1–3) and distribution of the tax revenues among the purchasers – groups 1 and 4 (group 4) – as an equal subsidy on per-area (per pre-management withdrawals) basis. The distribution of absolute and proportional benefits from groundwater management for each of the five strategies is given in Table 5.

One should expect the GMA to encourage implementation of the first strategy: it seems to be the least-costly to administer and (assuming that the Gini coefficient is based on the proportional benefits from management) yields the smallest value of the Gini coefficient (η). However, this strategy, which favors groups 1 and 4 over groups 2 and 3, will probably be rejected by groups 2 and 3 as an inequitable quota-allocation mechanism (an unequal quota per unit of any relevant variable). Among the other strategies considered (which are all based on an equitable allocation mechanism), the third (second) would be preferred (least preferred) by group 1; the second (fifth) would be preferred (least preferred) by group 3; and the fifth (second) would be preferred (least preferred) by group 4. The fact that the second strategy is considered to be the worst by groups 1 and 4 (who farm 60% of the basin's farm land), and that it yields the highest values of η, suggest its rejection. The last three strategies should be negotiated among the basin's farmers, taking into account their associated η values and administrative costs (the administrative costs associated with strategies 4 and 5 are probably the same, and they are higher than those associated with the third strategy). Although the basis for agreement is substantial because all groups stand to gain, the question of who will gain the most is highly dependent of the allocation strategy, and so a complicated and tedious negotiating process is expected.

It should be emphasized that strategies 2–5, which have been presented for demonstration purposes, are only a few of the many. Quotas can be assigned on the basis of variables other than those presented and, of course, the sale tax per unit can be changed.

Summary

Several management tools can be used to regulate groundwater withdrawals, with no one tool dominating the others in terms of efficiency of water use. However, this paper demonstrates that welfare redistribution effects vary substantially among management schemes, and different users may find considerably different schemes attractive. The equity problems associated with the division of management benefits must be undertaken with considerable care and resolved by consensus, probably involving extensive and complicated negotiations among users, which gives rise to bargaining cost.

It was found that imposition of constant (Pigouvian) pump tax equal to the marginal user cost, without rebate, will impose losses on each individual user. The empirical results suggest that these losses may be quite substantial. If rebates are considered, they have to be related to variables other than the quantities actually pumped. An equitable rebate scheme necessitates an equal per-unit rebate for an agreed-upon relevant variable. The selection of such a variable should take account of its associated measurement costs and its associated redistribution of management benefits as expressed by the Gini Coefficient, η. It is the job of the groundwater management agency (GMA) to come up with an agreed-upon basis for the calculation of η (e.g. absolute vs. proportional management benefits). The results of Table 4 demonstrate that the distributional consequences are extremely sensitive to the adopted rebate mechanism.

The variable-tax scheme was not found to be very attractive. It is very complicated to administer, and is expected to raise significant equity problems.

If groundwater extractions are controlled by a system of efficient quotas which differ among users, then all the benefits accrue to the pumpers. Although this strategy is relatively easy to administer, and yields a low value of the Gini coefficient (Table 5), one should expect its rejection as an inequitable allocation mechanism (an unequal quota per unit of any relevant variable). All other strategies presented are based on equitable quota-allocation mechanisms in conjunction with a policy aimed at inducing efficient water use whereby water rights can be sold to and bought from the GMA at a price of MUC_s. In addition, under two of these strategies, an equal sale tax (on a per-unit basis) is levied on sellers of water rights and the tax revenues distributed among the purchasers of water rights as an equal per-unit subsidy. It is demonstrated by the results of Table 5 that the above-mentioned strategies are quite different in their attractiveness to individual users, their associated Gini coefficients and their administrative costs.

The author of this paper is not in a position to recommend a particular management scheme. Each scheme involves 'losers' and 'winners' while 'losers' under one scheme might be 'winners' under another. The actual scheme is probably dependent on the relative political strength of the different user groups and the power of the GMA to lead and direct the negotiations among users to a mutually agreed-upon compromise. Although the negotiations are expected to be quite complicated, there is a considerable basis for agreement because all groups stand to gain and the question is ‘only’ who will gain the most.[6]

Clearly, all management schemes are costly to implement. The costs include information-gathering on economic and hydrologic parameters, monitoring water meters, tax administration, and greater management authorities or powers. Additional (and to some degree non-quantifiable) costs include: (a) Externality costs due to group choice processes, where the decisions reached are not unanimous. Thus, under simple majority voting, a small majority of users may choose a management scheme which, while benefiting slightly the majority, may impose heavy penalties on the minority. (b) Bargaining costs (see footnote 4). (c) Enforcement costs. Problems of enforcing the management scheme adopted are likely to occur. In fact, incentive for non-compliance with basic management arrangements abound. The GMA may employ a variety of economic and non-economic sanctions on the noncomplying member, all of which imply a certain cost to users as well as to the GMA.

All the above-mentioned cost components, which are not explicitly considered in this paper, should be estimated (as well as possible), included in the theoretical analysis, and compared with the benefits from groundwater management. The relevant guideline for instituting groundwater management is, obviously, that benefits exceed the costs.

Another direction in which the analysis might profitably be extended beyond agricultural groundwater use is the inclusion of municipal and industrial uses. The water-use conflict throughout the West is not only among farmers but between farmers and growing urban demands (Nunn, 1985). The conceptual model described in this paper can serve as a building block in such an extended analysis.

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Appendix

The first-order necessary conditions of the optimization problem (3) are:

$$a_i - b_i W_{ti} = eh_t + \alpha J'(h_{t+1})\frac{(1-\theta)}{As} \quad \text{for every } i \text{ and } t \tag{A1}$$

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[6] If the choice of the actual management scheme is not really based on group choice processes but is more an administrative decision on what values exist for decision, then the term $\sum \pi_t^i$ in the maximization problem (equation 3) should be replaced by $\sum \lambda_i \pi_t^i$, where λ_i $(0 \leqq \lambda_i \leqq 1)$ reflects the political strength of the ith group.

where J' is the partial of J. The left hand side represents the derived demand for groundwater of the ith farmer. The first term on the right hand side is the marginal pumping cost and the second term is the marginal user cost (MUC) implied by an increase in future pumping lifts. Now, recognizing W_{ti} as an implicit function of h_t through (A1), differentiating (3) and using the first-order conditions yields:

$$J'(h_t)=\sum_i\,[a_i-(b_i+e)W_{ti}]+\alpha J'(h_{t+1}) \tag{A2}$$

It is useful to consider now the steady states (SS).[7] By definition, a steady state occurs when pumping levels and pumping lifts remain unchanged over time. Let W_{si} and h_s be the SS pumping level of the ith farmer and the SS lift under optimal control, respectively:

$$J'(h_s)=\sum_i [a_i-(b_i+e)W_{si}]/(1-\alpha) \tag{A3}$$

As a result the SS marginal user cost, MUC_s, is:

$$\text{MUC}_s=\frac{eW_s(1-\theta)}{Asr} \tag{A4}$$

where $W_s=\sum_i W_{si}$. The SS under *optimal control* is given by:

$$a_i-b_i W_{si}=eh_s+\text{MUC}_s \quad \text{or} \quad h_s=\frac{a_i-b_i W_{si}}{e}-\frac{R}{Asr} \tag{A5}$$

$$W_s=R/(1-\theta) \tag{A5$'$}$$

In the absence of management, under *competition*, individuals have no incentive to account for the effect of their pumpings on future lifts and the marginal user costs are ignored. Hence, the SS under competition is given by:

$$a_i-b_i W_{si}=eh_s^* \quad \text{or} \quad h_s^*=\frac{a_i-bW_{si}^*}{e} \tag{A6}$$

$$W_s^*=R/(1-\theta) \tag{A6$'$}$$

where the superscript * represents a competitive 'management' scheme.

Let π_s^i and π_s^{*i} be the annual net benefits of the ith farmer under optimal control and competition, respectively. It can be readily verified that:

$$(\text{BGWM})_s^i=\sum_{t=1}^{\infty}\alpha^t[\pi_s^i-\pi_s^{*i}]=\frac{\text{W}_{si}(\text{MUC})_s}{r} \tag{A7}$$

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[7] It is mathematically convenient to consider the steady state, but it should be pointed out that steady-state solution is not necessarily a unique optimum in an economic sense.

where $(\mathrm{BGWM})_s^i$ represents benefits from groundwater management in the steady state.

For the sake of simplicity it is assumed that the current $(t=1)$ pumping lift is identical to the SS pumping lift under optimal control (h_s). Under this assumption, present value of net benefits under optimal control, B_i, is:

$$B_i = \sum_{t=1}^{\infty} \alpha^t \pi_s^i = [a_i W_{si} - \tfrac{1}{2} b_i W_{si}^2 - e h_1 W_{si}]/r$$

By tedious but straightforward algebra, it can be shown that the present value of net benefits under competition, B_i^*, are equal to:

$$B_i^* = \sum_{t=1}^{\infty} \alpha^t \pi_t^i = \frac{\alpha K_0^i}{1-\alpha} + \frac{\alpha K_1^i}{1-\alpha C_1} + \frac{\alpha K_2^i}{1-\alpha C_1^2}$$

where

$$K_0^i = \frac{e C_0 (e C_0 - 2 a_i (1-C_1)) + a_i^2 (1-C_1)^2}{2 b_i (1-C_1)^2}$$

$$K_1^i = \left(h_1 - \frac{C_0}{1-C_1} \right) \frac{e(e C_0 - a_i (1-C_1))}{b_i (1-C_1)}$$

$$K_2^i = \frac{e^2}{2 b_i} \left(h_1 - \frac{C_0}{1-C_1} \right)^2$$

$$C_0 = \frac{(1-\theta) \sum_i (a_i/b_i) - R}{As} \quad \text{and} \quad C_1 = 1 - \frac{(1-\theta) e \sum_i (1/b_i)}{As}$$

It can be shown that $|C_1| < 1$ is sufficient to guarantee convergence to h_s^*.

Actual benefits from groundwater management, $(\mathrm{BGWM})^i$, are given by:

$$(\mathrm{BGWM})^i = B_i - B_i^* \qquad \text{(A8)}$$

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