Potential for groundwater management: Gisser-Sanchez effect reconsidered

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[1] This paper revisits Gisser-Sanchez's effect, a paradoxical empirical result that persists in the groundwater literature since 1980, when it was first identified by Gisser and Sanchez. In essence, Gisser-Sanchez's effect (GSE) states that the numerical magnitude of benefits of optimally managing groundwater is insignificant. This paper critically reviews both the theoretical and empirical attempts to address GSE. It highlights the fact that in the theoretical literature the single most important cause for the presence of GSE is the prevalence of very steep marginal groundwater use benefit curves, which imply that groundwater usage is not very sensitive to price changes. However there exist circumstances that its effects can be eliminated. Thus the case for different theoretical investigations is put forward. Moreover, this paper also points at various misconceptions, inaccuracies, and omissions of the current state of the literature that could potentially resolve part of the existing puzzle.

INDEX TERMS: 6329 Policy Sciences: Project evaluation; 6339 Policy Sciences: System design; 6399 Policy Sciences: General or miscellaneous; *KEYWORDS:* Gisser-Sanchez effect, groundwater management, optimal control

1. Introduction

[2] Gisser-Sanchez's effect (GSE) refers to a paradoxical empirical result, present and persisting in the dynamic solutions of groundwater exploitation under different extraction regimes, since 1980. Namely, although serious depletion of aquifers is a major threat to many freshwater ecosystems all over the world, the social benefits from managing groundwater extraction are numerically insignificant. Clearly, if GSE extends to a general rule then the role and scope of water management are severely limited. This is even more evident when we take into consideration that implementing optimal extraction is not going to be costless.

[3] When groundwater withdrawals exceed recharge, the resource will be mined over time until either supplies are exhausted or the marginal cost of pumping additional water becomes prohibitive. The first implication of this is that a marginal user cost is associated with mining groundwater, reflecting the opportunity cost associated with the unavailability in the future of any unit of water used in the present. An efficient allocation considers this user cost, which effectively signals the in situ scarcity of the resource and is called the resource's scarcity rents. Hence efficient pricing of a resource that exhibits natural supply constraints, incorporates both marginal cost of extraction and scarcity rents. Scarcity rents must be imposed on current users.

[4] Figure 1 graphs this argument. The dotted line depicts marginal extraction costs for existing, conventional water sources, such as irrigation wells. If these sources were not available, the alternative would be a backstop source such as desalination, which we assume to be available in unlimited quantities though at the high (and constant) cost ($\bar{p}$). Suppose that, contrary to the common situation, all rights to in situ groundwater could be owned and sold independently of the overlying land. The shadow price of groundwater would be bounded at the high end by what prospective buyers are willing to pay (the buyer can either purchase water rights covering an existing source, with extraction cost ($q_{Gt}c$), or develop the backstop at cost ($q_{Gt}\bar{p}$); thus for the incremental source at capacity (q_{Gt}), the buyer's maximum willingness to pay for existing rights is represented by the distance ($c\bar{p}$)) and at the low end by what sellers are willing to accept (the basis for determining owners' reservation price is the awareness that if today's rate of use increases by one unit, the buyer will incur sooner the higher costs of supramarginal wells). At (marginal) capacity (q_{Gt}), potential scarcity rent is the distance ($c\mathbf{l}$). The efficiency price line shows the efficient price for water, incorporating extraction costs as well as scarcity rents.

[5] Given the difficulty of establishing clear groundwater ownership rights, scarcity rents frequently go unrecognized and are difficult to estimate [see, e.g., *Groom et al.*, 2003, 2004; *Koundouri*, 2003; *Koundouri and Xepapadeas*, 2003, 2004; *Koundouri and Pashardes*, 2002]. Ignoring scarcity rents means that the price of groundwater is too low and extraction is above the socially optimal level. In the absence of optimal dynamic management of common-pool groundwater resources, or alternatively in the presence of a competitive extraction regime, ignoring scarcity rents results in inefficient pricing and misallocation of the resource. (Competitive behavior need not be myopic. The problem is not

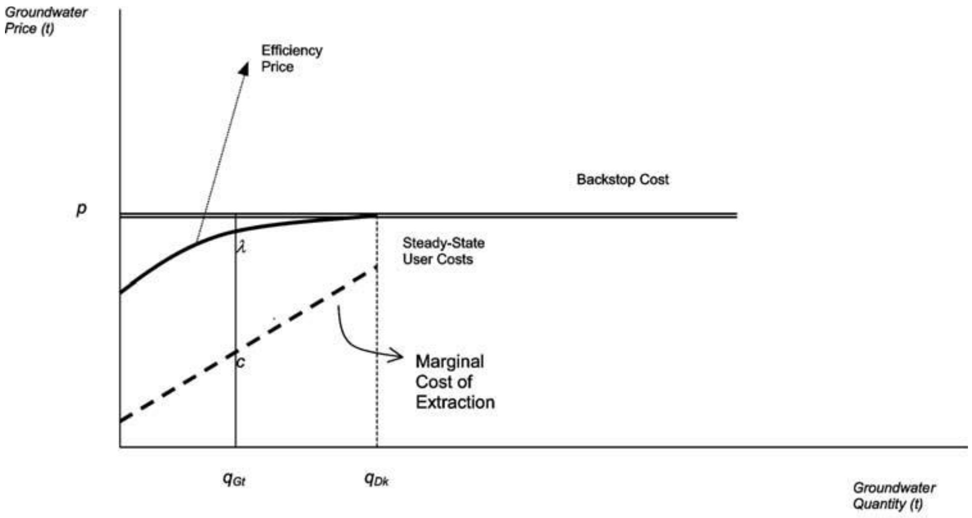

Figure 1. Extraction cost, scarcity rents, and efficiency price of groundwater.

with the market mechanism, but the property rights institution. However, this misuse seems to be fairly commonplace in this literature, so we will not interfere with its perpetuation and hope that readers will suffer this imprecision.)

[6] A number of possible rationalizations of GSE can be offered: (1) the hydrogeological physical structure of aquifers is such that eliminates this externality, (2) the marginal benefit curve derived from groundwater use is very steep and as a result not significantly sensitive to increases in the price of the resource implied by adding marginal scarcity rents to marginal extraction costs, (3) the marginal value of groundwater in situ scarcity is insignificantly small and as such it does not cause significant behavioral changes in the market for water, (4) another positive externality is involved in groundwater extraction that reduces the effect of common property externalities, and/or (5) there is a major fault in the way the literature attempts to measure management benefits. The main aim of this survey is to investigate which of the above rationalizations are empirically relevant and identify additional factors that could potentially reduce or eliminate this effect.

[7] In section 2, we discuss the motivation of *Gisser and Sanchez*'s [1980a, 1980b] work, replicate their model and present their results. In section 3, we examine the robustness of GSE in a game theoretic framework, i.e., when the interaction between extracting agents is explicitly taken into account. In section 4, we review empirical studies that examine the robustness of GSE under nonlinear water demand and cost functions, under variable economic relations and endogenous rates of change, and under conjunctive use of surface and groundwater and stochastic recharge. Section 5 concludes the survey.

2. Gisser-Sanchez Model

2.1. Motivation

[8] Problems of groundwater allocation have been studied in the context of the theory of mine by a number of economists including *Milliman* [1956], *Renshaw* [1963], and *Kelso* [1961]. Then, *Burt* [1964, 1966, 1967, 1970], in a notable series of papers, has drawn on principles of inventory management to derive decision rules for the optimal temporal allocation in a dynamic programming format. Extending Burt's work, *Bredehoeft and Young* [1970] have incorporated a complex groundwater model, accounting for the heterogeneity of a hypothetical aquifer, into a simulation program representing a groundwater basin system, and studied the effects of different policy instruments that might correct the misallocation of commonly owned groundwater. They found that net benefits from 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 specific yield of the aquifer. *Brown and Deacon* [1972] derived a formula for a tax that should be imposed on groundwater (pumped) in order to yield the optimal control solution. Then, *Brown* [1974] recognized the issue of congestion externality in aquifers with open access characteristics, and suggested a charging tax to correct this inefficiency.

[9] At the same time other economists studied competitive solutions to the problem of temporal allocation of groundwater, where scarcity rents are completely dissipated by users. *Gisser and Mercado* [1972, 1973], in an extension of the work by *Kelso* [1961] and *Cummings and McFarland* [1973], showed that in a free market, farmers will pump until the aquifer reaches an unacceptable water level. When this point is reached, farmers will either import supplemental water or be restricted to use a smaller amount of water by being assigned water rights. Assuming however, that at some future time farmers might reach the bottom of the aquifer anyway, they might want to consider optimal regulation of pumping at times earlier than the actual time of reaching the bottom. This argument poses an optimal control problem and warrants a solution that should be compared with the case of no control. This was the departure point for Gisser and Sanchez's work in 1980.

2.2. Model

[10] The basic model analyzed by Gisser and Sanchez is a simplified representation of the economic, hydrologic and agronomic facts that must be considered relative to the irrigator's choice of water pumping. Figure 2 illustrates a one-cell model of an aquifer, known as a ''bathtub,'' which characterizes the hydraulic aspects of Gisser and Sanchez's

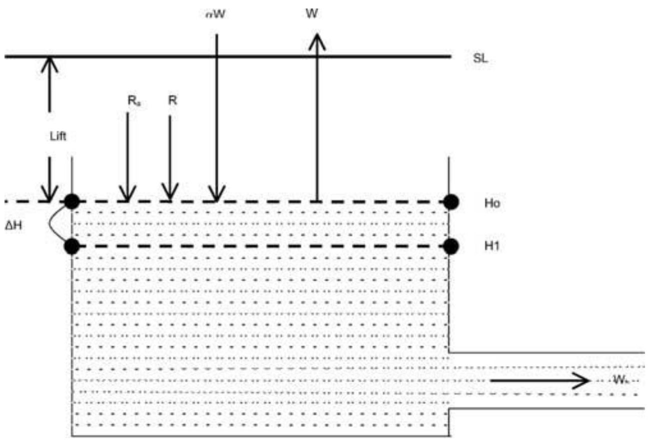

Figure 2. A model of an aquifer. Adapted from *Gisser* [1983] (reprinted with permission of the University of Chicago Press).

model. More precisely, the aquifer in Gisser and Sanchez's work is modeled as an unconfined aquifer, with infinite hydraulic conductivity. (Infinite hydraulic conductivity implies that the aquifer will never dry up, irrespective of groundwater extraction rates, which is equivalent to the assumption of a bottomless aquifer. Gisser and Sanchez justified their adoption of the bottomless aquifer assumption by arguing that it is implied by the standard assumption in the literature that time goes to infinity. However, if this is not the case a steady state solution might not be reached. Moreover, *Zimmerman* [1990] showed that the optimal pumping rate can be substantially lower when the hydraulic conductivity is small enough to result in a significant cone of depression around the well.) Moreover, constant return flow is assumed, which, in the presence of fixed irrigation technology, suggests constant rate of water application. Then, deterministic and constant recharge is assumed, which, in conjunction with the assumption of constant return flow, implies constant types of land use, independence of surface water and groundwater systems, and constant average rainfall. Moreover, sunk costs, replacement costs, and capital costs in general are ignored, and it is implicitly assumed that energy costs are constant. It is also implicitly assumed that the well pump capacity constraint is nonbinding. Finally, exclusiveness in Gisser and Sanchez's model is achieved by assuming that only land overlying the aquifer can be irrigated, i.e., the demand curve does not shift to the right over time. Overall, the explicit recognition of the assumptions behind GSE attempted in this paragraph, indicates that the model and its results shown below, should be used with caution on real aquifer systems. The definition of the parameters in Figure 1 and the estimates of the pertinent ones of the Pecos Basin in New Mexico, where Gisser and Sanchez applied their model, are given in the Table 1.

[11] In Gisser and Sanchez's model natural discharge was assumed to be a linear function of H as given below:

$$W_n = a + bH \tag{1}$$

The numerical estimates for the parameters a, b for the Pecos Basin were estimated at $a = -4{,}008{,}000$ acre feet per annum, and $b = 1200$ acre feet/foot per annum. The demand curve for irrigation water was assumed to be a well-behaved negatively sloped linear function:

$$W = g + kP \tag{2}$$

where P is the price in dollars. For the Pecos Basin the values of demand parameters were estimated by *Gisser and Mercado* [1972] at $g = 470{,}635$ acre feet, and $k = -3{,}259$ acre feet per dollar. Further, it was assumed that the cost of pumping water is a linear function and from Figure 1 it follows that

$$P = C_0^0 + C_1^0(S_L - H) \tag{3}$$

where C_0^0 represents fixed costs and C_1^0 is the marginal pumping cost per acre-foot per foot of lift. Letting $C_0 = C_0^0 + C_1^0(S_L - H)$ and $C_1 = -C_1^0$ then:

$$P = C_0 + C_1 H \tag{4}$$

For the Pecos Basin $S_L = 3{,}550$ feet, the dynamic draw-down of the confined aquifer was estimated at 20 feet and the cost of lifting one acre-foot per foot of lift was estimated at \$0.035, which gives $C_0 = \$125$ and $C_1 = -\$0.035$ per acre foot per foot. Substituting equation (4) into (2), gives:

$$W = d + kC_1 H \tag{5}$$

where $d = g + kC_0$. The differential equation that describes the water table as function of time in Gisser and Sanchez's paper is obtained by equating ''rate in'' minus ''rate out'' as given in

$$AS\frac{dH}{dt} = R + R_a + (\alpha - 1)W - (a + bH) \tag{6}$$

Substituting (5) into (6) gives:

$$AS\frac{dH}{dt} = [(\alpha - 1)kC_1 - b]H + [R + R_a + (\alpha - 1)d - a] \tag{7}$$

where $R_a = 0$, unless supplemental water is artificially recharged. Equation (7) is a linear nonhomogeneous equation and its solution governs the behavior of farmers under competition. The solution is given by

$$H = x + y\exp[rt] \tag{8}$$

where the lengthy expressions for x,y and r are given in Appendix A. Farm net income is obtained by

Table 1. Extraction Cost, Scarcity Rents, and Efficiency Price of Groundwater

Symbol	Description	Numerical Estimates for Pecos Basin
H	water table	
R	natural recharge	173,000 acre feet per annum
R_a	artificial recharge	
W	water pumped	
W_n	natural discharge	
α	coefficient of return flow	0.27
AS	storativity of the aquifer	135,000 acre feet per foot
S_L	average level of irrigation	3,550 feet above sea level

integrating the demand for water and subtracting pumping costs:

$$G(t) = u + \upsilon\exp(\rho t) + \omega\exp(2\rho t) \qquad (9)$$

where the expressions for u, υ and ω are given in Appendix A.

[12] As illustrated in Figure 1 in the introductory section, under competition farmers will not incur the scarcity rents of the resource they consume, that is, they will pump water at the rate determined by the point of intersection between demand for water and the marginal cost of pumping, thereby. The present value of future income streams under competition is denoted by PVC and is given by:

$$PVC = \int_0^{t_m} G(t)\exp(-\rho t)dt + \int_{t_m}^{\infty} G_m\exp(-\rho t)dt \qquad (10)$$

where m is the time at which steady state is reached (which is assumed to be the bottom of the aquifer), ρ is the discount rate and

$$G_m = \frac{1}{2k}W_m^2 - \frac{g}{k}W_m - (C_0 + C_1H_m)W_m$$

The explicit expression for PVC is given in Appendix A.

[13] Again, as indicated in Figure 1, given the common property aspect of this problem, it is necessary to levy a charge of λ per unit extracted, which is the scarcity value of the stock of the resource. The optimal control solution of the problem does exactly this. The governing differential equation is equation (6), the water table level $H(t)$ is the state variable, water pumped $W(t)$ is the control variable and the performance criterion to be maximized is the present value of future income streams:

$$C(W) = \int_0^{\infty}\left[\frac{1}{2k}W^2 - \frac{g}{k}W - (C_0 + C_1H)W\right]\exp(-\rho t)dt \qquad (11)$$

The Hamiltonian associated with this optimal control problem is:

$$\mathcal{H}(t;H;W;\lambda) = -\exp(-\rho t)\left[\frac{1}{2k}W^2 - \frac{g}{k}W - (C_0 + C_1H)W\right] + \lambda\frac{R + (\alpha - 1)W - (a + bH)}{AS} \qquad (12)$$

Using the Pontryagin Principle and differentiating over time, one can obtain the following nonhomogeneous linear system of differential equations for the optimal $H(t)$ and $W(t)$, respectively:

$$\frac{dH}{dt} = -\frac{b}{AS}H + \frac{\alpha - 1}{AS}W + \frac{R - a}{AS};\quad H(0) = H_0$$

$$\frac{dW}{dt} = -C_1k\left(\rho + \frac{2b}{AS}\right)H + \left(\rho - \frac{b}{AS}\right)W + \frac{kC_1(R - a) - (g + kC_0)(b + \rho(AS))}{AS} \qquad (13)$$

2.3. Simulation Results

[14] Given the above hydro-economic model, Gisser and Sanchez used a discount rate of 10 percent and simulated the intertemporal water pumpage for Pecos Basin (H_0 = 3400 feet), once under the assumption of competition and once under the assumption of optimal control. The results from their simulations were as follows:

Competition

$$H(t) = 3223 + 177.7\cdot\exp(-0.0095t)$$

$$W(t) = 430536 + 20274\cdot\exp(-0.0095t)$$

$$C(W) = \$3.085\times10^8$$

Optimal Control

$$H(t) = 3223.5 + 176.5\cdot\exp(-0.0095t)$$

$$W(t) = 428260 + 20020\cdot\exp(-0.0095t)$$

$$C(W) = \$3.080\times10^8$$

Notice that the trajectories under the two regimes are almost identical and the two figures for wealth (present value of future income streams) are practically identical. This result led Gisser and Sanchez to conclude that there is no substantive quantitative difference between socially optimal rules for pumping water and the so-called 'competitive' rates; hence the welfare loss from intertemporal misallocation of pumping effort is negligible. This conclusion amounts to Gisser-Sanchez's Effect.

[15] Solving analytically Gisser and Sanchez's model one can see that if equation (14) holds, then the rate of discount will practically vanish from the exponents of the optimal control formulation of the problem. Thus the exponents of the optimal control result will be practically identical with the exponents of the competition result. This analytical derivation implies that as long as the slope of the (uncompensated) groundwater demand curve is small relative to the aquifer's area times it's storativity, then GSE will persist.

$$\left(\frac{kC_1(\alpha - 1)}{AS}\right)^2 \approx 0 \qquad (14)$$

[16] The upshot of this result is obvious: if there is no quantitative difference between optimal and competitive rates of water pumping, then policy considerations can be limited to those which ensure that the market operates in a competitive fashion and concerns relative to rectifying common property effects are obviated. This is even more evident when we take into consideration that implementing optimal extraction is not going to be costless. In other words, GSE establishes that the inefficiency of private exploitation is not a sufficient condition for public intervention since regulation of the resource would have to be based on an accurate cost-benefit analysis. This suggests that there is little or no role for water policy in the form of pumping limitations. At issue, of course, is whether current rates of groundwater depletion are ''premature in

any sense. To the extent that they are, then these observations are clearly dichotomous.

3. Robustness of GSE With Dynamically Interacting Agents

3.1. Game Theoretic Models of Pumping Behavior

[17] The policy implications of GSE arose considerable concerns that led to a number of attempts to refine the model by adopting more realistic assumptions. As indicated in the first paragraph of section 2, Gisser and Sanchez's model builds on a number of restrictive assumptions that put into question its real world relevance. In section 4, we critically review the empirical results from various attempts to revise the model according to more realistic assumptions. A relevant issue, is that Gisser and Sanchez's model does away with any form of interaction between the extracting agents. However, during the last twenty years economists have recognized that the theory of dynamic games provides an extremely powerful framework for studying many of the classic questions in resource extraction. It provides the possibility to model the dynamic interactions involved in the allocation of scarce natural resources with common property characteristics. It also provides the ability to account for the fact that most externalities exhibit some form of structural time dependence; that is, not only the flow of external effects is important for the level of environmental damage and depletion, but also the stock or concentration of external effects. This development was also employed for the characterization of pumping behavior when the number of extracting players is small. Interesting inference on the robustness of GSE can be derived by comparing steady state groundwater level under (1) optimal control, (2) uncontrolled strategic interaction, and (3) uncontrolled nonstrategic interaction.

[18] *Dixon* [1989], *Negri* [1989], and *Provencher and Burt* [1993] discuss game theoretic models of pumping behavior under common property arrangements. In such a framework, a firm's strategy is the groundwater extraction plan defining its behaviour in each period of its planning horizon. An equilibrium in Nash strategies is a set of (M) admissible groundwater extraction plans, the jth element of which maximizes the value of groundwater to the jth firm, given the other ($M - 1$) groundwater extraction plans in the set. The precise nature of the equilibrium depends on whether firms pursue 'path' or 'decision rule' strategies. Nash equilibria in path strategies reflect the inclination of firms to take the extraction paths of the other firms exploiting the resource as given. Nash equilibria in decision rule strategies reflect the inclination of firms to take the decision rules of the other firms exploiting the resource as given. In essence, path and decision rule formulations of players' strategy spaces correspond to extreme assumptions about players' abilities to make commitments about their future actions. The use of path strategies corresponds to the assumption that commitments extend over the entire future horizon; the use of decision rule strategies corresponds to the assumption that no commitment at all is possible.

[19] It is now becoming apparent that Nash equilibria in path strategies are not good approximations of extracting behaviour. It is doubtful that under the common property regime the firms exploiting the groundwater resource will jointly commit to a set of path strategies, especially in light of the stochastic processes which place a premium on flexibility in decision making. Given that firms usually base their extraction decisions on the observed state of nature, decision rules seem to be a more realistic description of actual behavior and as a result appear more prominently in the groundwater literature. The relevant equilibrium concept for decision rules is a type of Markov-Nash equilibria, in which the decision rules of firms at time (t) are a function of only the current values of the state variables. As shown by Negri, path strategies capture only the pumping cost externality whereas decision rule strategies capture both, the pumping cost externality and the strategic externality, and exacerbates inefficient aquifer exploitation. In general, *Provencher and Burt* [1993] conclude that the steady state groundwater reserves attained when firms use decision rules strategies are bounded from below by the steady state arising from competition and from above by the steady state arising from optimal exploitation. (*Dixon* [1989] examined alternative equilibria involving decision rule strategies known as punishment strategy (trigger strategy) equilibria. These equilibria are typically (though not necessarily) characterized by the result that aggregate welfare is maximized by the credible threat of all firms to pump groundwater at sub-optimal rates if any firm defects from the optimal rate of groundwater pumping. However, when the number of firms using the groundwater resource is large, trigger strategy equilibria are unlikely to evolve.)

[20] However, these results are different from those obtained by other authors, such as *Tsutsui and Mino*'s [1990] in the field of industrial economics or *Dockner and Long* [1993], *Wirl* [1994], and *Wirl and Dockner* [1995] in the field of environmental economics. They find that there exist equilibria in decision rules strategies, which approach the optimal control solution more than path strategies. These precedents let *Rubio and Casino* [2004] to adapt the model defined by Gisser and Sanchez in order to examine whether strategic behavior plays against the efficiency of the solution, as established by Negri and Provencher and Burt, or for the efficiency of the solution, as seemed to happen in Tsutsui and Mino's, Dockner and Long's, and Wirl's papers. Their findings show that strategic behavior plays against the efficiency of private exploitation, but they also confirm the robustness of GSE in a game theoretic framework. In particular, in Rubio and Casino's simulations for the Texas High Plains Basin, the effect of dynamic inefficiency was found less than 5.5 feet for a discount factor of 0.1 and 11 feet for a discount factor of 0.05. These amount to negligible welfare difference between competition and optimal control.

3.2. Tradeable Permits Regulation

[21] The remedy usually prescribed by the literature for the inefficiencies arising in common property groundwater extraction, is central (optimal) control by a regulator, who uses taxes or quotas to obtain the efficient allocation of resource over time. When differential games are used, the instrument considered to implement the full-coopera-

tive outcome is, apart from side payments, a tradeable permit scheme. In the context of groundwater depletion *Young and Bredehoeft* [1972], *Smith* [1977], *Gisser* [1983], *Anderson et al.* [1983], *Provencher* [1993] (in particular, *Provencher* [1993] examined in a deterministic setting the applicability of the tradable permit scheme for the case where the groundwater resource is already pumped ''too deep,'' that is, beyond the optimal steady state, and the task of the regulator is to return the water table to its optimal steady state), and *Provencher and Burt* [1993, 1994] suggested a similar institutional arrangement in which private shares to the groundwater stock are established. Firms are granted an endowment of tradeable permits to the in situ groundwater stock, which they control over time. Each firm's bundle of permits represents its private stock of groundwater. This private stock declines due to groundwater pumping and increases to reflect the firm's share of periodic recharge. It also changes in response to the firm's activity in the market for groundwater stock permits, increasing when permits are purchased and decreasing when permits are sold. As a practical matter, the market price for permits serves to allocate groundwater over time.

[22] This particular regime is economically inefficient; both the pumping cost externality and the risk externality (the latter arising in stochastic frameworks, where groundwater is treated as a buffer to surface water drought; see section 4.3) persist after the allocation of permits. (The inefficiency of the private property rights regime let economists to generally overlook this regime as a means to manage resources like groundwater. For instance, *Dasgupta and Heal* [1979] discuss the futility of privatizing fugitive resources like groundwater and oil. Their argument concerned regimes granting firms entitlements to particular units of the resource. As argued above however, in the private property rights regime proposed in the groundwater literature, a firm is entitled to a particular number of units of the resource, via its endowment of permits, but is not entitled to particular units of the resource.) Moreover, this regime is time-inconsistent. (As argued by *Provencher* [1993], ''.. . the most problematic aspect of the private property rights regime is not its economic inefficiency... but rather its time-inconsistency''. Time inconsistency is the conundrum faced by regulators whose optimal policy depends on the initial state of nature. For example, the positive price of groundwater stock permits is derived not from the regulator's initial allocation of stock permits, but rather from the regulator's initial allocation of stock permits implied by the first binding minimum. Typically the minimum water table that maximizes welfare given the current state of the resource is not the same one that would maximize welfare given the state of the groundwater resource in the future. This conundrum reflects the time inconsistency of policy instruments [*Kydland and Prescott*, 1977]. In the context of the implementation of the private groundwater property rights regime, a credible solution to the time inconsistency problem, suggested by *Provencher and Burt* [1994], is to set the minimum water table at its steady state level, as determined from the regulator's optimization problem, and to deny the regulator the discretionary power to change this minimum. In a strict sense this approach is usually suboptimal, but it nonetheless goes a long way to ensuring the viability of the private property rights regime.) However, attempts to quantify the value of groundwater resource under both central (optimal) control and the private property rights regime indicate that groundwater privatization recovers most of the potential gain from management. In particular, in *Provencher*'s [1993] programming model of Madera County California this regime recovered 95% of the potential gain from management. (Although *Provencher*'s [1993] theoretical model was formulated in a deterministic framework, he used a stochastic dynamic programming model for his empirical analysis. The only source of uncertainty that he introduced in his empirical model is the stochastic delivery of the Central Valley Project to one of the groundwater basins he considered in his three-cell aquifer model.) Likewise, in a somewhat more complicated stochastic dynamic programming model of the same region, *Provencher and Burt* [1994] found that the private property rights regime recovers about 80% of the expected welfare gain from groundwater management. Given that under a private property rights regime both the pumping cost and the risk externalities persist, these findings may be attributed to the fact that this regime is more capable than others to exploit the private information held by firms.

[23] Significantly, although the private property rights regime recovers a relatively large proportion of the potential gain from groundwater management, this gain is relatively small and GSE remains robust. In particular, *Dixon* [1989] found that control raised the net benefit of groundwater in the Kern County California by 0.3%, *Provencher* [1993] found that control raised the value of groundwater resource of Madera County California by 2 – 3% and *Provencher and Burt* [1994] by 4 – 5 percent for the same basin. In this regard, the simulated value of groundwater stock of the Central Valley under the private property rights regime, is the latest contribution to the recent literature finding low returns to groundwater management.

[24] Still, the conclusion that there is no need to manage groundwater resources would be premature. As argued in section 2.2, a number of the assumptions underpinning Gisser and Sanchez's model are unrealistic. In the next section, we review a variety of empirical investigations, which, at least in part considered the robustness of GSE. Most of them attempted to empirically test refined versions of the model, which moved away from the assumptions of linear demand and cost functions, and allowed for variable economic relations and endogenous rates of change. Moreover, the low returns to groundwater management in Kern and Madera Counties, where game-theoretic extractive models were tested, may reflect the large surface water delivery to the county. In areas where surface water deliveries are not so large, or where future surface water supplies dwindle as water is redirected to urban uses, groundwater management could yield large welfare gains. Finally, when firms are risk averse the private property rights regime offers potential benefits from risk management not available under the common property arrangement. For these two reasons, section 4 also reviews recent developments in the groundwater literature that not only acknowledge the

stochastic nature of groundwater recharge in their theoretical representations, but they also take into account the hydrologic link between surface water and groundwater resources.

4. Testing the Robustness of GSE

[25] *Noel et al.* [1980] found that control increases the value of groundwater in the Yolo basin in California by 10%. *Lee et al.* [1981] found that control raised the net benefit of groundwater in the Ogallala basin by only 0.3%. *Feinerman and Knapp* [1983] derived empirical estimates of benefits from groundwater management in Kern County in California, which were quite sensitive to the water demand schedule and interest rate. However, in all cases considered the increase in welfare from groundwater management was at most 10%. *Nieswiadomy* [1985] utilized empirically the difference equation (6), in order to calculate annual water pumpage at the county level from primary data. Then, using these water pumpage calculations, he estimated a water demand equation and tested GSE. Although his results indicated that groundwater management in the Texas High Plains would be unwarranted, he proceeded with a sensitivity analysis on present value profits using different slope and intercept values for the groundwater demand curve. This analysis showed that benefits from groundwater management do not increase monotonically as the absolute value of the slope increases.

4.1. Nonlinear Water Demand and Cost Functions

[26] A basic assumption in Gisser and Sanchez's model is the linearity of the demand curve for water. To study the relative importance of this assumption for GSE, *Allen and Gisser* [1984] compared optimal control and no-control strategies using a nonlinear demand curve and the same data. This comparison confirmed for the case of the nonlinear demand function what had been demonstrated by GSE for the case of a linear demand function. Moreover, Allen and Gisser argued that optimal control may be impossible in the real world because the true demand curve is not really known. In particular, they graphically demonstrated that even if simulated optimal control yields slightly better results than no control, a strategy of no control is likely to yield better results than optimal control, unless one can be sure that the estimated demand for groundwater is very close to the true demand.

[27] *Worthington et al.* [1985], however, applied dynamic programming to a model of a confined aquifer underlying the Crow Creek Valley in southwestern Montana, to determine an optimal interseasonal allocation of groundwater extraction. Their simulation results suggested that the difference between the two regimes may not be trivial if the relationship between the average extraction cost and the water table level is not linear. Although in most groundwater studies a linear marginal pumping cost relationship is assumed, in the case of a confined aquifer existing artesian pressure introduces an interval of sharp curvature in the marginal cost function, making linear cost curves unrealistic approximations of the underlying cost structure. In addition, Worthington et al. illustrated that the difference between the two regimes may not be trivial if there are significant differences in land productivity. When land is assumed to be homogeneous, the gross returns function with respect to water use tends to be nearly linear. But with greater heterogeneity in productivity, the returns function is more concave, and differences in the optimal use policy under a common property setting are more pronounced. Hence the need of more theoretical work to resolve an asymmetric groundwater pumping differential game where the differences in land productivity are taken into account.

4.2. Allowing Variable Economic Relations and Endogenous Rates of Change

[28] Implicit in Gisser and Sanchez's model and in follow up research are the assumptions of fixed economic relations (e.g., time-independent demand) and/or exogenous and constant rates of change (e.g., constant and fixed exogenous crop mix, constant crop requirements, fixed irrigation technology (notable extensions are *Burness and Brill* [1992] and *Shah et al.* [1995], who considered endogenous irrigation technology choice), constant energy costs, constant exogenous types of land use, constant hydrologic conditions). As in any long-run study however, projected results become more tenuous as the steady state is approached. Estimated benefit and cost functions used in the simulations of GSE may bear little relation to the actual benefit and cost functions when economic, hydrologic and agronomic conditions are much different. More complex representations of increasing resource scarcity incorporate opportunities for adaptation to the rising resource prices that signal scarcity. In the long-run, adoption of new techniques, substitution of alternative inputs, and production of a different mix of products offer rational responses to increasing scarcity.

[29] *Kim et al.* [1989] developed an *n*-stage optimal control model, that incorporated the opportunity for adaptation to resource depletion. The demand for irrigation groundwater was disaggregated into crop-specific linear demand curves. As the intertemporal shadow price of groundwater increased in a mining era, the number of irrigated crops diminished in stages. The model suggested two supplementary traits to a conventional intertemporal depletion path: the relative allocation of groundwater among irrigated crops and endogenous switch times describing an intertemporal cropping pattern. Both planning and common property equilibria were derived and compared empirically. From an application to Texas High Plains the transition away from irrigation of sorghum to dryland agriculture occurs twice as fast when done optimally. However, benefits from groundwater management were as small as 1 – 3.7% as the interest rate varied from 5 – 2%. Thus GSE persists even when the opportunity of adaptation to resource depletion is incorporated in the analysis. Extending this model, *Koundouri* [2000] and *Koundouri and Christou* [2000] analyzed the optimal management of an aquifer, with stock-dependent extraction cost and a backstop substitute, facing multisector linear demands. Application to the Kiti aquifer in Cyprus demonstrates that the presence of a backstop technology diminishes the importance of management benefits (3.8%), while its absence makes optimal control significantly welfare increasing (409.4%). The latter result is attributed to the near depletion state of the aquifer under consideration.

[30] *Brill and Burness* [1994] found that a 2% annual demand growth laid to significant divergence (16.85%) in socially optimal versus competitive rates of groundwater pumping in Ogallala aquifer. In addition, their work supported existing evidence indicating that high social discount rates diminished the importance of (future) pumping cost externalities and produced a convergence between competitive and planning pumping rates. In a follow up study, applied to Curry county, one of the five counties covered by the Ogallala aquifer, *Burness and Brill* [2001] considered a model with endogenous investment in irrigation technology. However, its numerical simulation revealed only a modest difference between benefits in the planning vis-a-vis the competitive solution. The welfare gains from more efficient water use are offset to some extent by inefficiencies in investment.

4.3. Conjunctive Use of Stochastic Surface Water and Groundwater

[31] The first and most extensive studies of conjunctive use of surface water and groundwater are by *Burt* [1964, 1966, 1967, 1970], where groundwater stocks are modeled as partially renewed by a stochastic process. Burt's analysis however, modeled surface water and groundwater as substitute goods, abstracting from the problems associated with the lagged hydrologic effect present in a tributary aquifer. (A tributary aquifer is characterized by a groundwater stock that is hydrologically connected to a body of surface water. In such an aquifer, surface water may recharge the underground aquifer, or groundwater may supplement surface flows depending upon hydrological conditions.) *Burness and Martin* [1988] were the first to develop an analytical economic model which focused primarily on the hydrologic link between surface and groundwater, by modeling the instantaneous rate of aquifer recharge caused by groundwater pumping, through river effects. They modeled such river effects as externalities which reinforced groundwater overpumping present due to the usual common property effects. Their conclusion was that optimal policy requires compensation to be paid for both river effects and aquifer depletion net of river effects. This work points to an additional externality created by groundwater pumping that can be corrected with the appropriate management, and potentially eliminate GSE by increasing management benefits. However, Burness and Martin did not proceed to an empirical estimation of these benefits.

[32] Unfortunately, there exists no literature on models focusing primarily on the hydrologic link between ground and surface water and at the same time acknowledging the stochastic nature of surface water supplies. Instead, the literature that incorporates stochastic surface supplies into a groundwater model, adopted *Burt*'s [1964] framework. That is, surface water and groundwater are modeled as substitute goods, aquifers are not connected with surface water and they only benefit from substantial natural recharge. One of the interesting issues that arises in this context, is whether groundwater is more valuable in a stochastic setting than in a deterministic one.

[33] *Feinerman and Knapp* [1983] were the first to investigate the case of stochastic surface supplies which they assumed to be independently and identically distributed normal random variables. They found that the probability distribution of the lift converged to a steady state distribution with constant variance and a mean equal to the deterministic steady state. Moreover, expected benefits from groundwater management in Kern County in California under uncertainty, were found to be similar to expected benefits under certainty. As a result the authors did not pursue the uncertainty case any further.

[34] *Tsur* [1990] and *Tsur and Graham-Tomasi* [1991], however, argued that economic intuition suggests that groundwater is undervalued in a deterministic setting, because such a setting fails to consider the role of the resource as a buffer against surface water drought. This intuition was supported by simulations for the Negev Desert in Israel reported by Tsur and Graham-Tomasi. The authors found that the buffer value of groundwater ranged from 5% to 84% of the total value of the resource, depending on extraction costs, the variability of surface water inflows, and aquifer size. Ignoring the aquifer's buffer value creates a risk externality. This externality ultimately arises because the income risk of water-using firms is affected by the total amount of groundwater stock available for pumping. Each additional unit of groundwater stock available for future consumption lowers income risk of all firms by increasing the buffer against risk, provided by the total amount of groundwater stock available for future pumping. But of course, in its decision-making a firm considers only the private benefit of risk reduction, and consequently fails to extract groundwater at the socially optimal rate.

[35] Interestingly however, the positive sign on the buffer value is an empirical result, not a theoretical one. That is, one cannot rely solely on microeconomic 'first principles' to prove that groundwater is undervalued in a deterministic analysis; additional assumptions are necessary. Under central (optimal) control the buffer value is positive if the firm-level unconditional expected present value of net revenues from groundwater consumption, is greater than the firm-level conditional (i.e., conditional on random surface water supplies being fixed at their means) expected present value of net revenues, for all feasible values of the groundwater stock. By Jensen's inequality, this relationship holds if the value function is convex in surface water supplies for all feasible values of groundwater stock. Although this is certainly plausible, and perhaps empirically prevalent, its violation does not violate the standard assumptions of the neoclassical paradigm. If we accept, however, that in the real world the buffer value of groundwater is usually positive, then deterministic analyses underestimate the benefits derived from managing this resource.

[36] Moreover, *Provencher and Burt* [1993, 1994] argued that managing groundwater by adopting the regime of private tradeable water permits, may generate considerable welfare in a stochastic framework by providing opportunities for risk management. Figure 3 provides an illustrative example of how the groundwater stock affects income risk. As drawn, it reflects the simplifying assumptions that surface water is delivered to firms at no cost and groundwater pumping is costless. Under these assumptions surface water and groundwater are perfect substitutes; thus there is no economical reason to distinguish among them in the

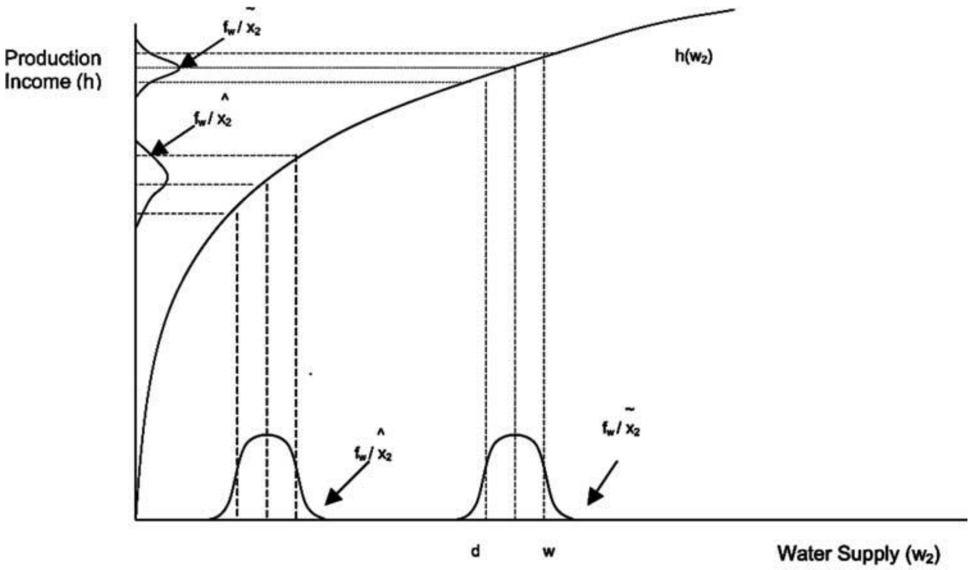

Figure 3. The effect of total groundwater stock on income risk. Adapted from *Provencher and Burt* [1994] (reprinted with permission of Blackwell Publishing).

production process. Production income (assumed to be monotonically increasing and concave function of water) in period 2 (of a two-period model) may be expressed as a function of only the firm's total water consumption, denoted by (w_2).

[37] Each of the (M) identical firms consumes ($w_2 = q_2 + x_2/M$) units of water in the terminal period, where (q_2) is each firm's random exogenous water allocation in period 2 and (x_2) is the basin-wide stock of groundwater in period 2. Hence the magnitude of the total groundwater stock has a mean-shifting effect on the distribution of the firm's water consumption, shown in Figure 3 by the two density functions of water consumption ($f_w | x_2$) and ($f_w | x_2$). These have the same shape but are positioned differently. The characterized by a high level of total carry-over stock (x_2), while the latter density function is characterized by a low level of total carry-over stock, (x_2). (All density functions in Figure 3 are associated with density axes that are suppressed for the sake of clarity.) The corresponding income density functions are identified by ($f_h | x_2$) and are obtained graphically by using the income curve ($h(w_2)$) to map the density function of water consumption into the probability space of production income. Figure 3 shows that insofar as production income is concave in water consumption, the distribution of a firm's income from productive activities is more compact, that is, less risky, at relatively high levels of total groundwater stock than at relatively low levels. The intuition behind this result is straightforward: when the stock of available groundwater is large, water is not scarce, and so productive activities are insensitive to the vicissitudes of surface water supply.

[38] Furthermore, the negative correlation between production income and income from groundwater stock permits (that is, water scarcity reduces production income but increases the price of groundwater stock permits, thereby increasing stock trade income) provides a means of risk management not available under central control. By Jensen's inequality, because the water revenue function is concave in water consumption, surface water inflows are more valuable when fixed at their mean value, than when drawn from the natural distribution of inflows. This result suggests the potential for welfare gains from ''smoothing'' surface water inflows. Note, however, that this rationale is diminished by the presence of groundwater, which is itself a source of water consumption ''smoothing''. In this context, the buffer value of groundwater is the welfare gain from postponing (perhaps indefinitely) those inflow-smoothing surface water projects which would prove economical to undertake immediately in the absence of groundwater. In other words, because groundwater is available, costly projects to smooth surface water flows, projects which would otherwise pass a benefit-cost test, are optimally postponed.

[39] The question that remains to be answered however, is whether the buffer value of groundwater is significant enough to eliminate GSE. The answer to this question turns on the relative magnitude of the buffer values under central (optimal) control and the common property arrangement. If the buffer value of the groundwater resource is about the same under the common property arrangement as under central control, the common practice of calculating the return to groundwater management in a deterministic setting provides a good estimate of the ''true'' return to management. Still, this is once again an empirical question. *Knapp and Olson* [1995] considered joint operation of a surface reservoir and groundwater aquifer, where reservoir inflows are stochastic and outflows can be used for irrigation or for recharge to the aquifer. By contrasting efficient groundwater use to common property use they find that common property withdrawals are larger than efficient withdrawals for similar values of the state variables, resulting in significantly greater pumping depths in the steady state. Despite this, however, they found that the benefits from groundwater management are relatively small. On the basis of these results, it seems that GSE prevails in stochastic frameworks as well. Interestingly however, the mean and standard deviation for annual net benefits in the limiting distribution

Table 2. Testing the Robustness of GSE

Source	Model	Welfare Gains	Basin/Location	Recharge
		1980 – 1985		
Gisser and Sanchez [1980a, 1980b]	baseline model	0.01% (r = 10%)	Pecos/New Mexico	negligible
Noel et al. [1980]	baseline model	10.00% (r = 10%)	Yolo/Calofornia	moderate
Lee et al. [1981]	baseline model	0.30% (r = 10%)	Ogallala/Texas	negligible
Feinerman and Knapp [1983]	baseline model	10.00% (r = 5%)	Kern/California	substantial
Allen and Gisser [1984]	nonlinear demand	0.01% (r = 10%)	Pecos/New Mexico	negligible
Nieswiadomy [1985]	baseline model	0.28% (r = 10%)	High Plains/Texas	moderate
Worthington et al. [1985]	variable productivity	28.98% (r = 6%)	Crow Gree/Montana	moderate
		1986 to Today		
Kim et al. [1989]	demand adaptation	1 – 3.7% (r = 5 – 2%)	High Plains/Texas	moderate
Dixon [1989]	stochastic DP	0.3% (r = 5%)	Kern/California	substantial
Provencher [1993]	stochastic DP	2 – 3% (r = 5%)	Madera/California	substantial
Brill and Burness [1994]	demand growth (2% p.a.)	16.85% (r = 1%)	Ogallala/California%	negligible
Provencher and Burt [1994]	stochastic DP	4% (r = 5%)	Kern/California	substantial
Knapp and Olson [1995]	stochastic OC	2.6% (r = 5%)	Kern/California	substantial
Koundouri [2000]	adaptation/near depletion	409.4% (r = 5%)	Kiti/Cyprus	negligible
Burness and Brill [2001]	substitutable technology	2.2% (r = 4%)	Curry/New Mexico%	negligible

Increases in	Effect on Welfare Gains
Sensitivity Analysis	
Aquifer area[a]	negative and moderate
Aquifer storativity[a]	negative and moderate
Surface inflow[a]	positive and small
Initial lifts[a]	negative and small
Energy costs[a]	positive and small
Interest rate[a]	negative and large
Demand intercept[b]	positive and Moderate
Demand slope[b]	positive and large

[a] See, for example, *Feinerman and Knapp* [1983].

[b] See, for example, *Nieswiadomy* [1985].

were $209 and $25 under optimal management, and $192 and $30 under common property. Hence optimal management does reduce the variability of returns, which indicates that benefits may be larger under risk aversion. This let *Knapp and Olson* [1996] to construct an empirical model with risk aversion. (Risk is pervasive in agriculture and as a result agricultural economists have frequently incorporated risk preferences into their analysis. Farmers with dynamic decision problems typically confront intrayear risk because profits are not deterministic in given decision-state combinations, and interyear risk because state transition processes are stochastic. However due to the inherent complexity of the problem of incorporating risk in the framework of dynamic programming, most researchers applying this technique have assumed that farmers are risk neutral.) Unfortunately, the first results are not very encouraging. They find that the effects of risk aversion are very small for the groundwater management problem.

4.4. Synopsis of Results

[40] Table 2 summarizes existing empirical evidence on the robustness of GSE. While different basins with various hydrologic characteristics and economic parameters were investigated, several general conclusions emerge. First, the possibility of negligible benefits from optimal groundwater management exists. Second, management benefits may differ from one basin to the next depending on the economic, hydrologic and agronomic parameters. Third, there exist converging lines of evidence as to the sensitivity of management benefits. As indicated in the sensitivity analysis in Table 2, management benefits are quite sensitive to the slope of the demand function and interest rate, moderately sensitive to aquifer storativity and size, and relatively insensitive to other parameters. Indeed, the sensitivity of GSE to the demand function is the central result that can be derived from reviewing this literature. However, this is not to say that there exist no need for groundwater management. On the contrary, in this section we have suggested a number of circumstances that have or may potentially render groundwater management significantly welfare increasing. These include nonlinear extraction costs, heterogeneous land productivity, nonstationary demand, situations of near aquifer depletion, presence of ‘‘river effects’’ and accounting for risk averse extracting agents.

5. Conclusions

[41] Indeed, the sensitivity of GSE to the demand function is the central result that can be derived from reviewing this literature. The GSE effectively states that if the slope of the demand equation is small relative to the storage of the aquifer, then the difference between the socially optimal and the private exploitation of the aquifer, is insignificant for all practical purposes. Even before the identification of GSE, a well-established view that *Kelso* [1961] has characterized as the ‘‘the water-is-different syndrome,’’ maintains that the derived demand for irrigation water is price inelastic (the absence of observations over a wide range of prices has necessitated the use of programming approaches to estimate the elasticities of the derived demand for water; many of these programming studies use linear programming [*Gisser and Mercado*, 1972; *Shunway*, 1973; *Montginoul and Rieut*,

1996]) or the positive nonlinear programming approach, which assumes that the cost of production is a quadratic function of acreage and reflects heterogeneity of land quality [*Howitt et al.*, 1980; *Bernardo et al.*, 1987; *Howitt*, 1995]. Arc elasticities of demand from quadratic programming studies range from −0.20 US $/acre-foot to −0.97 US $/acre-foot in California [*Howitt et al.*, 1980] and −0.22 US $/acre-foot to −0.40 US $/acre-foot in the Columbia Basin of Washington [*Bernardo et al.*, 1987]. On the whole irrigation demand curve estimates were found to be completely inelastic below a threshold price, and elastic beyond [*Shunway*, 1973; *Montginoul and Rieut*, 1996; *Garrido et al.*, 1997; *Varela-Ortega et al.*, 1998; *Iglesias et al.*, 1998; *Bontemps et al.*, 2004]. In general, this threshold price depends on climatic conditions and fluctuates between 0.13 US $/acre-foot for a ‘wet’ year and 0.79 US $/acre-foot for a ‘dry’ year. and thus changes in prices will redistribute income to or from farmers but not alter significantly water usage in agriculture. However, this is not to say that there exist no need for groundwater management. On the contrary, in this review we have suggested a number of circumstances that have or may potentially render groundwater management significantly welfare increasing. These include nonlinear extraction costs, heterogeneous land productivity, nonstationary demand, situations of near aquifer depletion, presence of ‘‘river effects’’ and accounting for risk averse extracting agents.

[42] Moreover, as it is obvious from the previous sections of this survey, the literature emphasizes the comparison between optimal pumping paths and common property outcomes. However, the value of water as a resource depends as much on the quantity available, as on its quality. Since additional externalities are present when quality is considered, it would be natural to suppose that intervention in such a case would yield a larger aquifer of better quality and possibly threaten the robustness of GSE. In a theoretical paper, *Roseta-Palma* [2002] adds a quality variable to a typical resource extraction model and analyzes the role played by groundwater quality-quantity interactions under optimal as well as private use. Roseta-Palma shows that the steady state optimal groundwater stock always becomes higher in quantity-quality than in quantity-only models. Furthermore, the private common property solution is characterized by smaller stock, lower quality, or both. Thus, if there is intervention by a central planner, at least one of the two features of an aquifer will improve, although there is the possibility that such an improvement in one of them is achieved at the expense of the other.

[43] Finally, *Pearce et al.* [2003] in a state-of-the-art review of the literature on declining long-run interest rates, indicate that uncertainty in the consumption growth rate and explicit recognition of the different range of individual preferences for the pure rate of time preference, which allows preferences for the present and future generations to be included, might be incorporated into a model of future discount rates, both of which, independently, lead to discount rates which decline with time. The impact of declining discount rates as already shown in GSE-related sensitivity analyses (see Table 2), will be to increase benefits of groundwater preservation to future generations, which could potentially eliminate the GSE. Concern over the effects of current policy decisions on future generations is also intensified by the presence of suspected irreversibilities. For example, think of the decision whether or not to irreversibly deplete an aquifer that has no use value in the present, but there is a possibility of developing into a major source of water in the future due to population growth or reduced rainfall; i.e., the aquifer has an option value. The uncertainty of future population growth combined with the exponential discounting process may result in very low weights being placed on benefits of protecting the aquifer. *Tsur and Zemel* [1995], however, found that uncertainty concerning occurrence of an irreversible effect has a profound effect. The expected loss due to the event occurrence is so high that it does not pay to extract in excess of recharge, even though under certainty (i.e., when the stock level below which the event occurs is known in advance) doing so would be beneficial. Thus uncertainty about the effect of extraction on future availability of the resource does eliminate GSE.

[44] The number of identified resolutions and possible paths for future research on GSE emphasizes the significance of developing realistic models for groundwater policy evaluation. Unfortunately, the difficulty of obtaining appropriate hydrologic and economic data, and the computational burden arising as state and decision variables are added to a model, remain barriers to the development of sophisticated dynamic optimization models. At best, current models provide only a general sense of the economic effects of various management prescriptions. The inability of most of these models to resolve the GSE suggests the need for creative, decentralized forms of management.

Appendix A

$$x = [a - (\alpha - 1)d - R]/[(\alpha - 1)kC_1 - b]$$

$$y = \{R - a + (\alpha - 1)d + [(\alpha - 1)kC_1 - b]H_0\}/[(\alpha - 1)kC_1 - b]$$

$$r = [(\alpha - 1)kC_1 - b]/AS$$

$$u = -d^2/(2k) - dc_1x - 0.5kC_1^2x^2$$

$$\theta = -dc_1 - kC_1^2x\ y$$

$$\omega = -kC_1^2y^2/2$$

$$PVC = (u/\rho)[1 - \exp(-\rho t_m)] + [\theta/(\rho - r)][1 - \exp((r - \rho)t_m)] + [\omega/(\rho - 2r)][1 - \exp((2r - \rho)t_m)] + (1/\rho)G_m \exp(-\rho t_m)$$

$$m = a - R + (1 - \alpha)d + [(1 - \alpha)kC_1 + b]x$$

$$n = [(1 - \alpha)kC_1 + b]y$$

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References

Allen, R. C., and M. Gisser (1984), Competition versus optimal control in groundwater pumping when demand is nonlinear, *Water Resour. Res.*, *20*, 752–756.

Anderson, T. L., O. R. Burt, and D. T. Fractor (1983), Privatizing groundwater basins: A model and its application, in *Water Rights: Scarce Resource Allocation, Bureaucracy, and the Environment*, edited by T. L. Anderson, pp. 1 – 16, Pac. Res. Inst. for Public Policy, San Francisco, Calif.

Bernardo, D. J., N. K. Whittlesey, K. E. Saxton, and D. L. Bassett (1987), An irrigation model for management of limited water supplies, *West. J. Agric. Econ.*, *12*, 164–173.

Bontemps, C., S. Couture, and P. Favard (2004), Is irrigation water demand really convex?, in *Econometrics Informing Natural Resource Manage-*

ment: Selected Case Studies, edited by P. Koundouri, Edward Elgar, Northampton, Mass., in press.

Bredehoeft, J. D., and R. A. Young (1970), The temporal allocation of ground water: A simulation approach, *Water Resour. Res.*, *6*, 3–21.

Brill, T. S., and H. S. Burness (1994), Planning versus competitive rates of groundwater pumping, *Water Resour. Res.*, *30*, 1873–1880.

Brown, B., Jr. (1974), An optimal program for managing common property resources with congestion externalities, *J. Polit. Econ.*, *82*, 163–173.

Brown, G., and R. Deacon (1972), Economic optimization of a single cell aquifer, *Water Resour. Res.*, *8*, 552–564.

Burness, H. S., and T. C. Brill (1992), The role for policy in common pool groundwater use, *Resour. Energy Econ.*, *23*, 19–40.

Burness, H. S., and T. C. Brill (2001), The role for policy in common pool groundwater use, *Resour. Energy Econ.*, *23*(1), 19–40.

Burness, H. S., and W. E. Martin (1988), Management of a tributary aquifer, *Water Resour. Res.*, *24*, 1339–1344.

Burt, O. R. (1964), Optimal resource use over time with an application to groundwater, *Manage. Sci.*, *11*, 80–93.

Burt, O. R. (1966), Economic control of ground water reserves, *J. Farm Econ.*, *48*, 632–647.

Burt, O. R. (1967), Temporal allocation of groundwater, *Water Resour. Res.*, *3*, 45–56.

Burt, O. R. (1970), Groundwater storage control under institutional restrictions, *Water Resour. Res.*, *6*, 1540–1548.

Cummings, R. G., and J. W. McFarland (1973), Groundwater management and salinity control, *Am. J. Agric. Econ.*, *56*, 830–836.

Dasgupta, P. S., and G. M. Heal (1979), *Economic Theory and Exhaustible Resources*, Cambridge Univ. Press, New York.

Dixon, L. S. (1989), Models of groundwater extraction with an examination of agricultural water use in Kern County, California, Ph.D. dissertation, Univ. of Calif., Berkeley.

Dockner, E. J., and N. V. Long (1993), International pollution control: Cooperative versus noncooperative strategies, *J. Environ. Econ. Manage.*, *24*, 13–29.

Feinerman, E., and K. C. Knapp (1983), Benefits from groundwater management: Magnitude, sensitivity, and distribution, *Am. J. Agric. Econ.*, *65*, 703–710.

Garrido, A., C. Varela-Ortega, and J. M. Sumpsi (1997), The interaction of agricultural pricing policies and water districts' modernization programs: A question with unexpected answers, paper presented at the 8th Conference of the European Association of Environmental and Resource Economists, Tilburg, Netherlands, 28–29 June.

Gisser, M. (1983), Groundwater: Focusing on the real issue, *J. Polit. Econ.*, *91*, 1001–1028.

Gisser, M., and A. Mercado (1972), Integration of the agricultural demand functions for water and the hydrologic model of the Pecos Basin, *Water Resour. Res.*, *8*, 1373–1384.

Gisser, M., and A. Mercado (1973), Economic aspects of ground water resources and replacement flows in semiarid agricultural areas, *Am. J. Agric. Econ.*, *55*, 461–466.

Gisser, M., and D. A. Sánchez (1980a), Some additional economic aspects of ground water resources replacement flows in semi-arid agricultural areas, *Int. Control, J.*, *31*(2), 331–341.

Gisser, M., and D. A. Sánchez (1980b), Competition versus optimal control in groundwater pumping, *Water Resour. Res.*, *16*, 638–642.

Groom, B., P. Koundouri, and T. Swanson (2003), The watershed economics management approach: An application to Cyprus, in *Economics of Water Management in Developing Countries: Problems, Principles and Policies*, edited by P. Koundouri et al., pp. 181 – 214, Edward Elgar, Northampton, Mass.

Groom, B., P. Koundouri, and T. Swanson (2004), Integrated resource management in Cyprus, in *Cost-Benefit Analysis and Water Resources Management*, edited by R. Brouwer and D. Pearce, Kluwer Acad., Norwell, Mass., in press.

Howitt, R. (1995), Positive mathematical programming, *Am. J. Agric.*, *77*, 329–342.

Howitt, R. E., W. D. Watson, and R. M. Adams (1980), A reevaluation of price elasticities for irrigation water, *Water Resour. Res.*, *16*, 623–628.

Iglesias, E., A. Garrido, J. Sumpsi, and C. Varela-Ortega (1998), Water demand elasticity: Implications for water management and water pricing policies, paper presented at the World Congress of Environmental and Resource Economists, Eur. Assoc. of Environ. and Resour. Econ., Venice, Italy, 26–28 June.

Kelso, M. M. (1961), The stock resource value of water, *J. Farm Econ.*, *43*(5), 1112–1129.

Kim, C. S., M. R. Moore, and J. J. Hanchar (1989), A dynamic model of adaptation to resource depletion: Theory and an application to groundwater mining, *J. Environ. Econ. Manage.*, *17*, 66–82.

Knapp, K. C., and L. J. Olson (1995), The Economics of conjunctive groundwater management with stochastic surface supplies, *J. Environ. Econ. Manage.*, *28*, 340–356.

Knapp, K. C., and L. J. Olson (1996), Dynamic resource management: Intertemporal substitution and risk aversion, *Am. J. Agric. Econ.*, *78*, 1004–1014.

Koundouri, P. (2000), Three approaches to measuring natural resource scarcity: Theory and application to groundwater, Ph.D. thesis, Fac. of Econ. and Polit., Univ. of Cambridge, Cambridge, U. K.

Koundouri, P. (2003), Contrasting different methodologies to deriving natural resource scarcity rents, in *Economics of Water Management in Developing Countries: Problems, Principles and Policies*, edited by P. Koundouri et al., pp. 157–178, Edward Elgar, Northampton, Mass.

Koundouri, P., and C. Christou (2000), Dynamic adaptation to resource scarcity with backstop availability, paper presented at the Tenth Annual Conference, Eur. Assoc. of Environ. and Resour. Econ., Rethymnon, Greece, June.

Koundouri, P., and P. Pashardes (2002), Hedonic price snalysis and selectivity bias: Water salinity and demand for land, *Environ. Resour. Econ.*, *23*(2), 45–56.

Koundouri, P., and A. Xepapadeas (2003), A new methodology to measuring groundwater scarcity: Theory and application, in *Economics of Water Management in Developing Countries: Problems, Principles and Policies*, edited by P. Koundouri et al., pp. 134 – 156, Edward Elgar, Northampton, Mass.

Koundouri, P., and A. Xepapadeas (2004), Estimating accounting prices for common pool natural resources: A distance function approach, *Water Resour. Res.*, *40*, W06S17, doi:10.1029/2003WR002170, in press.

Kydland, F. E., and E. C. Prescott (1977), Rules rather than discretion: The inconsistency of optimal plans, *J. Polit. Econ.*, *85*, 473–491.

Lee, K. C., C. Short, and E. O. Heady (1981), Optimal groundwater mining in the Ogallala Aquifer: Estimation of economic losses and excessive depletion due to commonality, report, Cent. for Agric. and Rural Dev., Iowa State Univ., Ames.

Milliman, J. W. (1956), Commonality, the price system and the use of water supplies, *Soc. Econ. J.*, *22*, 426–437.

Montginoul, M., and T. Rieut (1996), Instruments economiques et gestion de l'eau d'irrigation en France, *Houille Blanche*, *8*, 47–54.

Negri, D. H. (1989), The common property aquifer as a differential game, *Water Resour. Res.*, *25*, 9–15.

Nieswiadomy, M. (1985), The demand for irrigation water in the High Plains of Texas, 1957–1980, *Am. J. Agric. Econ.*, *67*(3), 619–626.

Noel, J. E., B. D. Gardner, and C. V. Moore (1980), Optimal regional conjunctive water management, *Am. J. Agric. Econ.*, *62*, 489–498.

Pearce, D., B. Groom, C. Hepburn, and P. Koundouri (2003), Valuing the uture: Recent advances in social discounting, *World Econ.*, *4*(2), 121–141.

Provencher, B. (1993), A private property rights regime to replenish a groundwater aquifer, *Land Econ.*, *69*(4), 325–340.

Provencher, B., and O. Burt (1993), The externalities associated with the common property exploitation of groundwater, *J. Environ. Econ. Manage.*, *24*, 139–158.

Provencher, B., and O. Burt (1994), A private property rights regime for the commons: The case for groundwater, *Am. J. Agric.*, 875–888.

Renshaw, E. F. (1963), The management of ground water reservoirs, *J. Farm Econ.*, *45*(2), 285–295.

Roseta-Palma, C. (2002), Groundwater management and endogenous water quality, *J. Environ. Econ. Manage.*, *44*, 93–105.

Rubio, S., and B. Casino (2004), Strategic behaviour and efficiency in the common property extraction of groundwater, *Environ. Resour. Econ*., in press.

Shah, F. A., D. Zilberman, and U. Chakravorty (1995), Technology adoption in the presence of an exhaustible resource: The case of groundwater extraction, *Am. J. Agric. Econ.*, *77*(2), 291–299.

Shunway, C. R. (1973), Derived demand for irrigation water: The California aqueduct, *Southwest. J. Agric. Econ.*, *5*, 195–200.

Smith, V. L. (1977), Water deeds: A proposed solution to the water valuation problem, *Ariz. Rev.*, *26*, 7–10.

Tsur, Y. (1990), The stabilization role of groundwater when surface water supplies are uncertain: The implications for groundwater development, *Water Resour. Res.*, *26*, 811–818.

Tsur, Y., and T. Graham-Tomasi (1991), The buffer value of groundwater with stochastic surface water supplies, *J. Environ. Econ. Manage.*, *21*, 201–224.

Tsur, Y., and A. Zemel (1995), Uncertainty and irreversibility in groundwater resource management, *J. Environ. Econ. Manage.*, *29*, 149–161.

Tsutsui, S., and K. Mino (1990), Nonlinear strategies in dynamic duopolistic competition with sticky prices, *J. Econ. Theory*, *52*, 136–161.

Varela-Ortega, C., J. M. Sumpsi, A. Garrido, M. Blanco, and E. Iglesias (1998), Water pricing policies, public decision making and farmers' response: Implications for water policy, *Agric. Econ.*, *19*, 193–202.

Wirl, F. (1994), The Ramsey model revisited: The optimality of cyclical consumption and growth, *J. Econ.*, *60*, 81–98.

Wirl, F., and E. Dockner (1995), Leviathan governments and carbon taxes: Costs and potential benefits, *Eur. Econ. Rev.*, *39*, 1215–1236.

Worthington, V. E., O. R. Burt, and R. L. Brustkern (1985), Optimal management of a confined aquifer system, *J. Environ. Econ. Manage.*, *12*, 229–245.

Young, R. A., and J. D. Bredehoeft (1972), Digital computer simulation for solving management problems of conjunctive groundwater and surface water systems, *Water Resour. Res.*, *8*, 533–556.

Zimmerman, W. R. (1990), Finite hydraulic conductivity effects on optimal groundwater pumping rates, *Water Resour. Res.*, *26*, 2861–2864.

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