Competition versus coopertion in groundwater extraction: A stochastic framework with heteregoneous agents

Marita Laukkanen

MTT Economic Research

Phoebe Koundouri

University of Reading and University College London

March 4, 2005

Abstract

We analyze a game with N farmers that extract groundwater from a common aquifer of small storage capacity. Our aim is to compare the socially optimal, myopic and feedback extraction strategies, the latter arising from competitive interaction between extracting agents. Our extension to existing literature is that we consider heterogeneous farmers, facing uncertainty deriving from stochastic rainfall. The farmers differ in terms of their choice of irrigation technology, which results in different farmer-specific impact on the aquifer recharge rate. We illustrate the implications of the different strategies on extraction rates, groundwater table levels and welfare attained, via simulations based on data from the Kiti aquifer in Cyprus.

Keywords: common property resources, groundwater management, difference games, strategic externality

JEL classification: D62, D99, Q15, Q25

1 Introduction

The most popular behavioral model in the groundwater literature is one in which farmers execute myopic pumping decisions; that is, the state equation does not enter the farmer's decision problem. Moreover, a large part of the literature focuses on comparing the steady-state groundwater level under myopic behavior (uncontrolled non-strategic interaction) and optimal control. See, for instance, Gisser and Sanchez (1980), Feinerman and Knapp (1983), Llop and Howitt (1983), Allen and Gisser (1984), Nieswiadomy (1985), Worthington et al. (1985). This focus derives from the need to explain the paradoxical Gisser-Sanchez (1980) result stating that although serious depletion of aquifers is a major threat to many freshwater ecosystems all over the world, the benefits from managing groundwater extraction that have been derived in empirical studies are numerically insignificant.

Koundouri (2000) shows that the Gisser-Sanchez result does not hold in an aquifer with small storage capacity. Moreover, in these aquifers, myopic groundwater pumping is not a good approximation of behavior, as externality effects are more noticeable. Dixon (1989), Negri (1989), and Provencher and Burt (1993) model uncontrolled strategic interaction (feedback solution) under the common property arrangement. In these models farmers' behavior is "memoryless" in the sense that each farmer's pumping behavior depends only on the current state of nature, and farmers take the state-dependent extraction rules[1] of their rivals as given. The empirical results from this literature indicate that the steady-state groundwater reserves attained when farms use feedback strategies are bounded from below by the steady-state arising when farms are myopic and from above by the steady-state arising from optimal exploitation.

Although there exist groundwater studies that take rainfall stochasticity into account (Burt, 1964, 1967, 1970; Provencher and Burt, 1994; Knapp and Olson, 1995, Fisher and Rubio, 1997; Zeitouni, 2004), non of them is solved in a game theoretic framework. What's more, none of these studies consider heterogeneous farmers. In our paper we consider a model that accommodates both strategic interaction between extracting agents and stochastic aquifer recharge, where recharge's stochasticity derives from stochastic rainfall. Each farmer makes his/her extraction choice facing uncertainty due to stochastic rainfall. Moreover, we consider heterogeneous farmers with respect to their choice of irrigation technology, which results in different farmer-specific impact on the aquifer recharge rate. The more efficient the chosen irrigation technology the smaller the return flow of water in the aquifer, but it is also true that the more efficient the farmer the less water he will extract from the aquifer for irrigation purposes.

The objective of this study is to compare the socially optimal extraction strategy with the feedback extraction solution and the myopic solution, when farmers are heterogeneous and interact under uncertainty deriving from stochastic rainfall. We illustrate the implications of the different strategies on extraction rates, groundwater table levels and attained welfare, via simulations based on data from the Kiti aquifer in Cyprus, which is an aquifer of small storage capacity. The results support Koundouri's (2000) finding that the Gisser-Sanchez result does not apply to small aquifers: our results indicate significant differences between the solutions arising from competition versus optimal extraction.

The chapter is structures as follows: In section 1 we develop the model of groundwater extraction with heterogeneous agents under stochastic recharge and solve the non-cooperative and social planner problems. In section 2 we apply both of these solutions, via simulation, on data from the Kiti aquifer in Cyprus and discuss the results. Section 3 concludes the paper.

1.1 Groundwater extraction under non-cooperation

We first examine non-cooperative extraction of groundwater, where each farmer makes her extraction decision without considering its effect on the other farmers' expected payoffs. There are no negotiations or understandings between the farmers. Each farmer maximizes her expected payoff, taking as given the other farmers' rates of extraction, which she can only infer from her knowledge of the other farmers' objective functions. Consider an aquifer where only the N farms with land overlying the aquifer have access to the resource. The farmers differ in terms of their choice of irrigation technology. By assumption, the farmers can be divided into two groups according to their efficiency and hence their effect on aquifer recharge rate: efficient farmers and inefficient farmers. Within each group, farms are identical in the sense that the profit function $\pi(q_{j,t})$ representing the benefits from groundwater extraction and the recharge rate α_k are identical for all the N_k, $k = e, i$, farmers in the group. The term $q_{j,t}$ denotes groundwater extraction by farmer j in period t, and the subscript $k = e, i$ refers to efficient and inefficient farmers. The per unit cost of groundwater pumping is determined by the level of the water table in period t, h_t. The costs of groundwater extraction, $c(h_t)$, then are identical for all the N farms. Farmer $j\prime s$ $(j = 1, ..., N)$ net revenue from water consumption is:

$$\pi_k(q_{j,t}) - c(h_t)q_{j,t} \tag{1}$$

By the assumption of farmers within each group being identical, the N_k farms in each group will pump the same amount of groundwater in period t,denoted by q_t^e and q_t^i,respectively for efficient and inefficient farmers. Total groundwater extraction in period t is then given by $N_e q_t^e + N_i q_t^i$. The state of the groundwater stock evolves according to:

$$h_{t+1} = g(h_t, \widetilde{R}_t, q_{t,}^e q_t^i) = h_t + \frac{1}{AS}[\widetilde{R}_t + (a^e - 1)N^e q_t^e + (a^i - 1)N^i q_t^i] \tag{2}$$

where $\widetilde{R}_t$ denotes periodic rainfall, A the area of the aquifer, S the storativity coefficient, and a^k, $k = e, i$ the recharge rate. The annual rainfall is a random variable. By assumption, the farmers' planning horizon is infinite. The discount factor used to trade off current and future net benefits is δ, where $0 < \delta < 1$.

There are two hypotheses we might entertain about the farms' decision problem when the aquifer is common property. If the agents are myopic, they do not consider the effect of their extraction on the groundwater stock. Each farm sets its extraction rate so as to balance the marginal net benefit of groundwater extraction and the unit cost of extraction:

$$\pi'_k(q_{j,t}) - c(h_t) = 0, \qquad k = e, i \tag{3}$$

When the number of extracting agents is relatively small, a more realistic description of pumping behavior would be that each agent considers the effect of its actions on the groundwater stock, but takes the other agents extraction plans as given. An individual agent's perception of the stock equation is:

$$h_{t+1} = g(h_t, \widetilde{R}_t, q^e_{t,} q^i_t) = h_t + \frac{1}{AS}[\widetilde{R}_t + (a^e - 1)[(N^e - 1)q^{e^*}_t + q^e_{j,t}] + (a^e - 1)N^i q^{i^*}_t] \tag{4a}$$

when agent j is of the efficient type, and

$$h_{t+1} = g(h_t, \widetilde{R}_t, q^e_{t,} q^i_t) = h_t + \frac{1}{AS}[\widetilde{R}_t + (a^e - 1)N^e q^{e^*}_t + (a^i - 1)[(N^i - 1)q^{i^*}_t + q^i_{j,t}] \tag{4b}$$

when agent j is inefficient.

The individual agent's problem then is to:

$$\max_{q_j} E[\sum_{t=0}^{\infty} \delta^t \{\pi_k(q_{j,t}) - c(h_t)q_{j,t}\}] \tag{5}$$

subject to the state equation (4a)/(4b). The dynamic programming equation for the agent's problem is:

$$V_k(h) = \max_{q_j} \left\{ \pi_k(q_j) - c(h)q_j + \delta E \left[V_k \left(g \left[h, \widetilde{R}, q^{e^*}, q^{i^*}, q_j \right] \right) \right] \right\} \tag{6}$$

The first-order necessary condition to the problem on the right side of (6) is:

$$\pi'_k(q_j) - c(h) + \delta E \left[\frac{a^k - 1}{AS} V'_k \left(g \left[h, \widetilde{R}, q^{e^*}, q^{i^*}, q_j \right] \right) \right] \tag{7}$$

Benveniste and Scheinkman's formula (1979) implies that

$$V'_k(h) = -c'(h)q_j + \delta E \left[V'_k \left(g \left[h, \widetilde{R}, q^{e^*}, q^{i^*}, q_j \right] \right) \right] \tag{8}$$

since $\partial g/\partial h = 1$. Equations (7) and (8) jointly determine the individually optimal rate of extraction q^{k^*}, for $k = e, i$, given the water table h_t and the distribution of the level of the water table under the individually optimal feedback extraction policy. The term $V'_k(g(.))$ represents the private shadow value of *in situ* groundwater, available in the next period. It depicts the agent's private user cost of pumping groundwater: each unit of groundwater extracted in the current period reduces the groundwater stock available for future consumption. An individual agent sets the marginal benefit of an additional unit of water extracted this year equal to the private user cost in terms of a reduced reserve of water available in the following year.

1.2 Social planner's solution

We next turn to the problem of central (optimal) control. Consider the case where there exists a single manager with the authority to control each firm's rate of extraction. The social planner's problem is to maximize the aggregate net benefit of groundwater extraction:

$$\max_{q_t^e, q_t^i} E \sum_{t=0}^{\infty} \delta^t [N^e \{\pi_e(q_t^e) - c(h_t)q_t^e\} + N^i\{\pi_i(q_t^i) - c(h_t)q_t^i\}] \tag{9}$$

subject to the state equation:

$$h_{t+1} = g(h_t, \widetilde{R}_t, q_t^e, q_t^i) = h_t + \frac{1}{AS}\left[\widetilde{R}_t + (a^e - 1)N^e q_t^e + (a^i - 1)N^i q_t^i\right] \tag{10}$$

There are N^e efficient agents and N^i inefficient agents among a total of N agents. Assuming that the social planner weighs each farmer's net benefits equally, the dynamic programming equation for the social planner's problem can be written as:

$$\begin{aligned} N^e V_e(h) + N^i V_i(h) = \max_{q^e, q^i}\{N^e[\pi_e(q^e) - c(h)q^e] + N^i\left[\pi_i(q^i) - c(h)q^i\right] \\ + \delta E[N^e V_e(g[h, \widetilde{R}, q^e, q^i] + N^i V_i(g[h, \widetilde{R}, q^e, q^i])]\} \end{aligned} \tag{11}$$

The first-order conditions are:

$$N^k\{\pi_k'(q^k) - c(h)\} + \delta E \frac{N^k(a^k - 1)}{AS}[N^e V_e'(g[h, \widetilde{R},)q^e, q^i]) + N^i V_i'(g[h, \widetilde{R}, q^e, q^i])] = 0 \tag{12}$$

for $k = e, i$. Dividing by N^k yields:

$$\pi_k'(q) - c(h) + \delta E \frac{(a^k - 1)}{AS}[N^e V_e'(g[h, \widetilde{R}, q^e, q^i]) + N^i V_i'(g[h, \widetilde{R}, q^e, q^i])] = 0 \quad (13)$$

for $k = e, i$.

Equation (13) together with the associated Benveniste and Scheinkman formula determines the socially optimal rates of extraction q^{k^*} for $k = e, i$ given the water table h_t and the distribution of the level of the water table under the socially optimal extraction policy. As in (8), $V_k'(g\,(.))$ represents the private shadow value of water left in the ground. In the social planner's solution, each farm's extraction rate is set to balance the marginal benefit of pumping in the current period to the opportunity cost it imposes on all agents in terms of a smaller reserve of water in the next period. A comparison of (7) and (13) shows that the individually optimal rate of groundwater pumping exceeds the socially optimal rate.

2 Application of the model

The application of the model uses data from the Kiti agricultural region, an aquifer with small storage capacity located in the coastal southern part of the semi-arid island of Cyprus. The notion of common property characterizes ownership of groundwater reserves, as the doctrine of absolute land ownership governs property law in the island. In particular, although the doctrine conditions ownership of groundwater on ownership of land overlying the aquifer (thereby limiting access), in all other respects owners of land own groundwater as a common property resource subject to the rule of capture.

2.1 The Data

Table 1 summarizes the hydrologic parameters for the region, supplied by the Water Development Department of Cyprus.

Table 1: Hydrologic Parameters

Parameter	Description	Parameter Value
a^e	Return flow coefficient of efficient farmers	0.1000 pure number
a^i	Return flow coefficient of inefficient farmers	0.4000 pure number
A	Area of the aquifer	12 000 000 m^2
S	Storativity coefficient	0.1250 pure number
$\widetilde{R}$	Rainfall	$\widetilde{R} \sim \Gamma(20.5, 24.4)$
h_o	Initial elevation of water table	3.45 m
SL	Maximum height of water table	47.5 m

The more efficient the irrigation technology the smaller the return flow of water in the aquifer. Empirical results on the efficiency of irrigation methods can summarized as follows. Irrigation efficiency for surface methods (basin, border, furrow irrigation) reaches 60%, for sprinkler irrigation (set systems, travelling guns, continuous move laterals) reaches 85%, and for localized irrigation (drip, micro-spayer) can reaches 95%. Most of the water not used by the plant is lost due to *deep percolation*, while a much lower percentage is lost by evaporation or run-off. For the area under consideration 12% of the farmers use surface irrigation systems, 8% use sprinkler irrigation systems and 80% use localized irrigation.[2] For simulation purposes, farmers that use the two most efficient technologies are grouped into one category and are called 'efficient', while the remaining less efficient farmers are grouped in a second category and are called 'inefficient'. The return flow coefficient for efficient farmers (a^e) is taken to be equal to the average of the return flow of the farmers that use sprinkler and localized irrigation system $\left[1-(\frac{85\%+95\%}{2})=0.1\right]$, assuming that evaporation is approximately equal to zero. The return flow coefficient for inefficient farmers (a^i) is equal to the return flow of the farmers that use surface methods $[1-60\%=0.4]$, again assuming that evaporation is approximately equal to zero.

The distribution of stochastic rainfall was estimated using a time series of rainfall in the Kiti region for the years 1927-2003. The mean of the series is equal to $493.21mm$ and the standard deviation is $109.67mm$. We used the test described by D'Agostino et al. (1990) with the empirical correction developed by Royston (1991) in order to identify the distribution from which our sample is coming from. This test indicates that at 98% confidence level we cannot reject the hypothesis that rainfall follows a gamma distribution.

Table 2 summarizes the socio-economic parameters for the region.

Table 2: Economic Parameters

Parameter	Description	Parameter Value
N	Total Number of farmers	60
N^e	Number of efficient farmers (85% of N)	51
N^i	Number of inefficient farmers (15% of N)	9
k_1	Cost of pumping per m^3 of water per meter of lift	$0.3500\ euros/m^3$
k_2	The intercept of the pumping cost equation	$0.3672\ euros/m^3$
g	Absolute value of the slope of agricultural water demand	$9,500,000\ m^3/euros$
k	The intercept of agricultural water demand	$3,500,000\ m^3$
$\pi(q_j)$	Benefit function for each farmer	$2.714q_j - 0.000014q_j^2$

The discussion in the previous paragraph indicates that 85% of the farmers in the area are efficient, while 15% of them are inefficient. The total number of farmers is 60. With regards to the groundwater demand curve we use the one estimated by Koundouri and Christou (2000). Given the absence of observations over a wide range of prices, the derived demand for groundwater by farmers was estimated by linear programming. From this demand curve we derive the individual farmer's demand curve and calculate the benefit function for each farmer. The marginal cost function used in the solution of the system is

$$c[h(t)] = k_2 - k_1 \cdot h(t),\ k_1 > 0 \tag{14}$$

The difference $(SL - h)$ measures pumping lift, the distance from the water table to the irrigation surface. This pumping cost function (a specific form of a general cost function) is very popular in the literature; e.g. Gisser and Mercado (1973), Kim et al. (1989). Its derivatives have the desirable properties: a positive partial derivative with respect to (q) and a negative cross-partial derivative between (q) and water table.

2.2 Simulation results

Simulations were carried out in Matlab 6.0 using the CompEcon Toolbox for Matlab (see Miranda and Fackler, 2002). CompEcon is a set of Matlab routines developed by Mario Miranda and Paul Fackler for solving a variety of dynamic problems in economics. Of particular interest to the problem at hand, the CompEcon routines for solving continuous time dynamic programming problems lend themselves to analyzing both the social planner's problem and the feedback solution to the N agent groundwater extraction game. The dynamic groundwater extraction model gives rise to functional equations whose unknowns are entire functions defined on a subset of Euclidean space. In many applications, such functional equations lack known closed-form solutions and can thus only be solved approximately using computational methods. Among the numerical functional equation methods, the collocation method provides a flexible, accurate and numerically efficient alternative (see e.g. Judd 1998, 1992, 1994). The CompEcon Toolbox provides a series of Matlab routines that perform the essential computations required in applying the collocation method.

Table 3 reports the numerical results for the steady state. The findings confirm Koundouri's (2000) result that in an aquifer of small storage capacity, competitive extraction results in serious depletion of the aquifer and significant welfare losses. In parallel to previous studies, the results indicate that a social planner would conserve the resource more than the status quo. Under optimal extraction, the mean elevation of the water table will approach 41 m, as opposed to the current level of 3.45 m. The feedback solution lies between the myopic solution and socially optimal extraction. However, as the number of farmers sharing the resource is fairly large, the feedback solution is close to the myopic one, and there is practically no difference in expected welfare arising from the two competitive policies. The predictions of the empirical model are grim in terms of the losses arising from competitive extraction. Under socially optimal extraction the expected welfare would be close to tenfold compared to the competitive outcome while the groundwater resource would be reserved. Compared to competitive extraction, the socially optimal solution allocates substantially more water to the inefficient relative to the efficient agents.

Table 3: Empirical Results

Policy	Extraction efficient farmers, m^3	Extraction inefficient farmers, m^3	Mean water table, m	Expected welfare, €
Myopic	155 300	155 300	2.7	113 100 000
Feedback	115 100	117 500	3.3	113 100 000
Social optimum	98 300	260 400	41	1 071 000 000

3 Discussion and extensions

We have extended the literature on groundwater extraction to consider the case of stochastic recharge to the aquifer and heterogenous agents. Our results, based on empirical data for the Kiti aquifer in Cyprus, indicate that competitive extraction results in significant welfare losses: social welfare under competitive extraction is 90 per cent lower than what could be attained under optimal management of the resource. Moreover, the groundwater resource is seriously depleted. Our results challenge the Gisser-Sanchez (1980) result that benefits from optimal (central) management are numerically insignificant. Substantial gains could be achieved through fully accounting for the effect of current extraction on future benefits from the groundwater resource.

Given that our results indicate significant differences between the solutions arising from competition versus optimal extraction, an interesting extension would be to investigate economic instruments that can be prescribed as remedies for the inefficiencies arising in the feedback solution. The remedy usually prescribed by the economics 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. Another instrument considered to implement the full cooperative outcome is a tradable permit scheme. In the context of groundwater depletion Provencher (1993) and Provencher and Burt (1994) examined the applicability of the tradable permit scheme in which private shares to the groundwater stock are established. In their framework, farms are granted an endowment of tradeable permits to the in situ groundwater stock, which they control over time. Each farm's bundle of permits represents its private stock of groundwater. This private stock declines due to groundwater pumping and increases to reflect the farm's share of periodic recharge. It also changes in response to the farm'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.

Notes

[1] An extraction rule expresses the groundwater pumping decision as a function of the observed groundwater stock

[2] Information provided by the Cyprus Ministry of Agriculture, Natural Resources and the Envionment.

References

[1] Allen, R. C., and Gisser, M., 1984. Competition versus optimal control in groundwater pumping when demand is nonlinear. Water Resources Research, 20, 752-6.

[2] Benveniste, L. and Scheinkman, J, (1979), 'On the Differentiability of the Value Function in Dynamic Models of Economies', Econometrica, 47, 727-732.

[3] Burt, O. R., (1964), 'Optimal resource use over time with an application to groundwater', Management Science, 11, 80-93.

[4] Burt, O. R., (1967), 'Groundwater management under quadratic irrigation function', Water Resource Research, 3,673-682.

[5] Burt, O. R., 1970. Groundwater storage control under institutional restrictions. Water Resources Research, 6, 1540-1548.

[6] D'Agostino, R. B., A. Balanger and R. B. D'Agostino, Jr., (1990), 'A suggestion for using powerful and informative tests of normality', The American Statistician 44 (4), 316-321.

[7] Dixon, L. S., (1989), Models of groundwater extraction with an examination of agricultural water use in Kern County, California, Unpublished Ph.D. dissertation, University of California.

[8] Dockner, E. J., and Long, N., (1993), 'International pollution control: cooperative versus noncooperative strategies', Journal of Environmental Economics and Management, 24, 13-29.

[9] Feinerman, E., and Knapp, K. C., 1983. Benefits from groundwater management: magnitude, sensitivity, and distribution. American Journal of Agricultural Economics, 65, 703-10.

[10] Fisher, A. C., and Rubio, S. J., (1997), 'Adjusting to climate change: Implications of increased variability and asymmetric adjustment costs for investment in water reserves', Journal of Environmental Economics and Management, 34, 207-227.

[11] Gisser, M., and Mercado, A., 1973. Economic aspects of ground water resources and replacement flows in semiarid agricultural areas. American Journal of Agricultural Economics, 55, 461-466.

[12] Gisser, M., and Sánchez, D. A., (1980), 'Competition versus optimal control in groundwater pumping', Water Resources Research, 31, 638-642.

[13] Judd, K. (1998), Numerical Methods in Economics, Cambride, MA: MIT Press.

[14] Judd, K. (1992), 'Projection Methods for Solving Aggregate Growth Models', Journal of Economic Theory, 58, 410-452.

[15] Judd, K. (1994), 'Approximation, Perturbation and Projection Methods in Economic Analysis', in Amman, H., Kendrick, D.A. and J. Rust (eds), Handbook of Computational Economics, Vol. 1, New York: North Holland, 509-586.

[16] Kim, C. S., Moore, M. R. and Hanchar, J. J., 1989. A dynamic model of adaptation to resource depletion: theory and an application to groundwater mining. Journal of Environmental Economics and Management, 17, 66-82.

[17] Knapp, K. C., and Olson, L., J., (1995), 'The economics of conjunctive groundwater management with stochastic surface supplies', Journal of Environmental Economics and Management, 28, 340-356.

[18] Koundouri, P., (2000), Three Approaches to measuring natural resource scarcity: Theory and Application to Groundwater, PhD Thesis, Faculty of Economics and Politics, University of Cambridge.

[19] Koundouri, P., and Christou, C. (2000). Endogenous Dynamic Adaptation to Resource Scarcity with Backstop Availability. Mimeo, University of Cambridge, UK.

[20] Llop, A. and Howitt, R., 1983. On the social cost of groundwater management: the role of hydrologic and economic parameters on policy actions. Unpublished Manuscript. University of California, Davis.

[21] Miranda, M. and Fackler, P. (2002), Applied Computational Economics and Finance, Cambride, MA:MIT Press.

[22] Negri, D. H., (1989), 'The common property aquifer as a differential game', Water Resources Research, 25, 1-15.

[23] Nieswiadomy, M., 1985. The demand for irrigation water in the High Plains of Texas, 1957-1980. American Journal of Agricultural Economics, 67(3), 619-626.

[24] Provencher, B., (1993), 'A private property rights regime to replenish a groundwater aquifer', Land Economics, 69 (4), 325-40.

[25] Provencher, B. and Burt, O., (1993), 'The externalities associated with the common property exploitation of groundwater', Journal of Environmental Economics and Management, 24,139-58.

[26] Provencher, B., and Burt, O., 1994. A private property rights regime for the commons: the case for groundwater. American Journal of Agricultural Economics. 875-888.

[27] Provencher, B., (1998), 'Issues in the conjunctive use of surface water and groundwater', In Daniel W. Bromley (ed), The Handbook of Environmental Economics.

[28] Royston, P., (1991), 'Tests for departure from normality', Stata Technical Bulletin, 2, 16-17. Reprinted in Stata Technical Bulletin Reprints, 1, 101-104.

[29] Royston, P., (1992), 'Approximating the Shapiro-Wilk W-test for non-normality', Statistics and Computing, 2, 117-119.

[30] Rubio, S.J., and Casino, B. (2001), 'Competitive versus efficient extraction of a common property resource: The groundwater case', Journal of Economic Dynamics and Control, 25, 1117-1137.

[31] Rubio, S.J., and Castro, J. P. (2000), 'Long run groundwater resource under uncertainty', Investigaciones Economicas, 20, 71-88.

[32] Tsur, Y. and Graham-Tomasi, T., (1991), 'The buffer value of groundwater with stochastic surface water supplies', Journal of Environmental Economics and Management, 21, 201-24.

[33] Tsur, Y., and Zemel, A. (1995), 'Uncertainty and irreversibility in groundwater resource management', Journal of Environmental Economics and Management, 29, 149-161.

[34] Tsur, Y., and Zemel, A., (2001), 'R&D policies for desalination technologies', Agricultural Economics, 24 (1), 73-85.

[35] Wirl, Franz (1994), 'Global warming and carbon taxes: Dynamic and strategic interactions between energy consumers and producers', Journal of Policy Modelling, 16, 577-596.

[36] Wirl, F. and Dockner, E., (1995), 'Leviathan governments and carbon taxes: Costs and potential benefits', European Economic Review, 39, 1215-1236.

[37] Tsutsui, S. and Mino, K., (1990), 'Nonlinear strategies in dynamic duopolistic competition with sticky prices', Journal of Economic Theory, 52, 136-61.

[38] Zeitouni, N., (2004), 'Optimal extraction from a renewable groundwater aquifer with stochastic recharge', Water Resource Research (forthcoming).