Groundwater and Ecosystems Damages: Questioning the Gisser-Sánchez Effect

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ABSTRACT

Gisser and Sánchez (1980a) state the conditions under which welfare gains from policy intervention are negligible in aquifer management, when compared with non-regulation or "free market" outcomes. This is the so-called Gisser-Sánchez effect (GSE), which has been supported by the ensuing literature during recent decades. The GSE requires a number of assumptions, among which is the disregard for aquatic ecosystems linked and dependent on aquifer systems. The depletion of aquifer systems in arid and semiarid regions worldwide is causing acute water scarcity and quality degradation, and leading to extensive ecosystem damages. This study shows that by including environmental damages into the analytical model, results can change substantially. The analysis highlights both theoretically and empirically the importance of policies in groundwater management, as well as the potential role for stakeholders' cooperation. The empirical application deals with two large aquifers in Spain, the Western La Mancha aquifer which is grossly mismanaged, and the Eastern La Mancha aquifer, which is moving towards sustainable management. Western and Eastern La Mancha aquifers illustrate that policies and institutions are essential to avoid the current global aquifer mismanagement.

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1. Introduction

The pressure on water resources has been mounting worldwide during the last century, creating problems in basins of rich and poor countries alike. This pressure is linked to the ever-increasing growth in population and economic activities at global scale. Although water integrity is an essential condition for having living rivers with healthy aquatic ecosystems, the pressure on water quantity and quality has been growing rapidly. The current situation is that water degradation is pervasive in many basins around the world, driven by the impacts of the escalating anthropogenic activities.

The problems created by the growing pressure of water extractions are twofold: one is water scarcity in local watersheds or whole basins created by excessive surface and groundwater withdrawals. The other is water degradation from pollution loads leading to many tracts of rivers and whole aquifers being spoiled, and losing their capacity to sustain ecosystem functioning and human activities.

In recent decades, water scarcity has become widespread in most arid and semiarid regions around the world, including river basins such as the Ganges, Indus, Yellow, Yangtze, Tigris, Euphrates, Nile, Amu and Syr Daria, Murray-Darling, Colorado and Rio Grande. Surface and subsurface resources in these river basins are being depleted and their quality degraded (World Water Assessment Programme, 2006). The scarcity problems in basins of arid and semiarid regions were created at first by extractions of surface waters, but at present they are compounded by the huge development of groundwater by individual wells, brought about by the adoption of pumping technologies with falling costs worldwide.

The region of the Indus, Ganges and Brahmaputra is the largest irrigated area in the world, expanding over 2.7 million ha in northern India, Pakistan, Bangladesh, Nepal and Eastern Afghanistan (Siebert et al., 2007). Groundwater overdraft in the region has been estimated at around 50 km^3 per year from satellite data (Tiwari et al., 2009). The problems created by this huge depletion of aquifers result from the declining water tables, and from the degradation of water quality by pollution loads or saline intrusion in coastal aquifers. One important health problem is the arsenic pollution detected in Bangladesh, which is poisoning the impoverished population in that country.

The Ogallala aquifer in the North American high plains covers 450,000 km^2 and supplies water to irrigate 5 million ha of land. Withdrawals for irrigation are 26 km^3 per year, which include an overdraft of around 10 km^3. The current storage amounts to 3,610 km^3 and the accumulated depletion is estimated at 310 km^3, with a water table decline that could attain up to 30 meters (McGuire, 2007). The only measure taken so far by federal, state and local public agencies is the monitoring of water level changes, but no control measures have been taken yet to stabilize or reduce overdraft.

Groundwater depletion in the Indus-Ganges basins and the Ogallala aquifer, together with groundwater depletion in places such as the Northern China plain Southwestern United States, Australia, Spain and Mexico, demonstrate that aquifer mismanagement is the rule, and that sustainable management of groundwater is a complex task that is very difficult to achieve. The reason behind the pervasive aquifer mismanagement worldwide is that groundwater is a common pool resource with environmental externalities. Adequate management can only be brought about by cooperation of stakeholders through the right institutional setting, rather than using pure economic instruments that are harder to implement in the case of public goods (Albiac, 2009).

The theory of depletable resources such as groundwater is an important field in economic theory, encompassing a large range of analytical results with major contributions on the sustainability of resources exploitation by Solow (1974), Dasgupta and Heal (1974), Stiglitz (1974), Hartwick (1977), and Common and Perrings (1992).[2] The problem of depletable resources arises because of the difficulties in establishing property rights in resources, leading to excessive resource depletion. The common pool nature of groundwater means that the open access by competing users creates the water extraction externality. Extractions by one user reduce the water stock available to others, and because every user believes that competitors will not conserve water for future use, there is no incentive to protect the water stock. This is the reason for market failure and the need for appropriate institutional arrangements to correct the failure. Therefore, the key issue in depletable resources is whether or not markets are capable of achieving a balanced intertemporal allocation of resources (Dasgupta and Heal, 1979).

The analysis presented here is based on the social welfare achieved under alternative aquifer management regimes. Social welfare is the difference between benefits and

[2] The arguments revolve around the degree of substitution between man-made capital and natural capital, with additional questions such as technical progress, backstop technologies, and uncertainty.

costs to society pertaining to the alternative patterns of resource use through time. Social benefits are the private profits of users, and social costs include both economic and environmental negative externalities. The procedure is to optimize social welfare in a model that includes all these externalities, and compare it with the solution under myopic individual pumping by users that disregard all externalities. A large difference calls for public intervention through policy measures (Howe, 2002). The externalities appearing when aquifers are exploited are 1) the extraction cost externality, which arises because users affect each other by lowering the water table and increasing the costs of extractions; and 2) the environmental externality, which arises because the depletion of large aquifer systems imposes environmental damages over linked ecosystems.

The contribution of this study is to take ecosystem damages into consideration in modeling aquifer management regimes. In the context of the intensive pressures on water resources described above, agents extract more water from aquifers than actual recharge, depleting the water storage and damaging the associated ecosystems. Decline in water tables cause progressive scarcity and quality degradation, and may lead to extensive loss of ecosystems.

Gisser and Sánchez (1980a, 1980b) analyzed aquifer management regimes and found that welfare gains from policy intervention are insignificant when compared with non-regulation or competitive outcomes. This study shows that by including environmental externalities into the analytical framework, together with the extraction cost externality, results can change substantially. The main analytical finding is that policies to control groundwater management are preferred to “free market” or non-regulation outcomes, provided that ecosystem damages are not neglected when relevant.

This finding is further examined with an empirical application to two large aquifers in Southern Spain, the Eastern and Western La Mancha aquifers, and the empirical results show large gains in welfare when correcting the market failures. While the Eastern La Mancha aquifer is moving towards sustainable management, the Western La Mancha aquifer is grossly mismanaged. The fall in the water table of Western La Mancha aquifer has lead to extensive destruction of wetlands and severe degradation of associated ecosystems, in particular the “Tablas de Daimiel” wetland, a National Park protected by UNESCO that is the second important wetland in the Iberian Peninsula. Both the theoretical analysis and the empirical analysis highlight the importance of policies and regulations in groundwater management, as well as the crucial need for institutional arrangements. Neither cooperation among stakeholders nor pure economic instruments will work without the appropriate institutional setting.

The article begins by presenting in section two an extension of the previous modeling effort by Gisser and Sánchez. This extended model accounts not only for the extraction costs externality caused by aquifer depletion, but also for the ecosystem damages externality from depletion. The purpose is to challenge the Gisser and Sánchez results by demonstrating that, under regulation, social welfare improves substantially over free market outcomes when ecosystem damages from depletion are important. Section three describes the Western and Eastern La Mancha aquifers, and compares the current management in both aquifers with three alternative management regimes. The first regime is "free market" with myopic pumping by agents that disregard both the extraction costs externality and the environmental externality. The second regime is partial cooperation with agents accounting for only the extraction costs of aquifer depletion. The third regime is full cooperation with agents accounting for both the extraction costs and the environmental externalities. Finally, the summary and conclusions are presented in section four.

2. Extending the Model of Gisser-Sánchez with Environmental Damages

Gisser and Sánchez (1980a) state a straightforward model of groundwater to compare two management alternatives for water allocation in an aquifer: one is free market or "laissez-faire," and the other is policy regulation or control. The analytical finding from their model is that the outcomes from free market or policy regimes are almost the same when aquifers are large enough. Gisser and Sánchez apply the model to the Pecos Basin of New Mexico, and the empirical results confirm the analytical findings. The conclusion is that policy regulation represented by the optimal control solution of groundwater management does not imply a perceptible increase in social welfare over free market. Therefore, any public intervention is not justified.

This result is known as the "Gisser-Sánchez effect" (GSE), which has been mostly confirmed by the ensuing literature (Burness and Brill, 2001; Dixon, 1989; Feinerman and Knapp, 1983; Knapp and Olson, 1995; Nieswiadomy, 1985; Provencher, 1993; Provencher and Burt, 1994). Koundouri (2004a, 2004b) summarizes this literature indicating that the GSE holds in most cases, although it is sensitive to the size of the aquifer and the specification of the water-demand function, which drives benefits. The validity of the GSE rests on the key assumption that the aquifer has to be quite large, and the secondary assumption of a small slope in the water-demand function.

A separate strand of the literature deals with groundwater quality, with contributions by Hellegers et al. (2001), Roseta-Palma (2002 and 2003), and Knapp and Baerenklau (2006). Hellegers et al. argue for water pricing to reduce groundwater pollution and to spur advanced irrigation technologies, and Roseta-Palma shows that open access is characterized by smaller storage, lower quality or both. However, these papers don't discuss whether free markets are good enough or if aquifers need policy intervention. Knapp and Baerenklau address the issue of welfare gains from policy regulation, and suggest greater efforts to manage groundwater than recommended from previous literature.

Gisser and Sánchez devise a dynamic model linking economic, hydrologic and agronomic variables of groundwater use. First, the demand and supply functions for irrigated water are defined, and these functions are connected with the hydrological characteristics of the aquifer. Then, the path of water allocation through time is calculated under the policy regime and the free-market regime, and results are tested empirically in the Pecos River Basin in New Mexico.

The water demand function is $W = g + k \cdot P$, where W is water extraction, P is water price, and g and k are the intercept and the price coefficient. The water supply is the pumping marginal cost function $P = C_0 + C_1 \cdot H$, where H is water table level, and C_0 and C_1 are the intercept and the water table coefficient (This is a reformulation of $P = C_0' + C_1'(S_L - H)$, where S_L is the elevation of the irrigation surface). The hydrological behavior of the aquifer is represented by the differential equation $AS \cdot \dot{H} = R + (\alpha - 1)W_t$ that explains the change in the water table $\dot{H}$, where R is natural recharge, α is the return flow coefficient, A is the area of the aquifer, and S is the storativity coefficient.

Under free market, farmers equate the current value of the marginal physical product of water ($P = \frac{g}{k} - \frac{1}{k} \cdot W$) with the current marginal cost of pumping ($P = C_0 + C_1 \cdot H$), without accounting for the water extraction cost externality. Using these two equations, together with the differential equation, the free-market solution for the water table H and the water extractions W are given by equations (1) and (2) in Table 1, where H_0 is the initial level of the water table at $t = 0$.

Under policy regulation, Gisser and Sánchez take into account the extraction cost externality. They formulate the optimal control problem by maximizing social welfare, defined by the present value of their collective private profits through time.

$$Max \int_0^{\infty} e^{-rt}\left[\frac{1}{2k}W_t^2 - \frac{g}{k}W_t - (C_0 - C_1 H_t)W_t\right]dt$$

$$s.t.\ \dot{H} = \frac{R + (\alpha - 1)W_t}{AS}, \qquad H(0) = H_0 \qquad (3)$$

where $\frac{1}{2k}W_t^2 - \frac{g}{k}W_t$ is farmers' revenue (the integral of the price dependent water demand equation) and r is the social discount rate. The solution equations for the water table H and for the water extractions W are given by equations (4) and (5) in Table 1, where $x_2 = \dfrac{r - \left[\left(r - 2kC_1\frac{(\alpha-1)}{AS}\right)^2 - 4\left(kC_1\frac{(\alpha-1)}{AS}\right)^2\right]^{1/2}}{2}$.

Gisser and Sánchez prove that the equations for the water table and for the water extractions are almost the same under free market and under policy regulation. They assume a very large aquifer with relatively large AS (area multiplied by storativity), and use this assumption to simplify the solution equations under policy regulation (4) and (5), until the resulting expressions equal the solution equations under free market (1) and (2).[3]

The intuition behind this result is that the free-market solutions (1) and (2) do not take the future into account, while the social planner solutions (4) and (5) do, and the differences are explained by the stock effect and discounting. When the aquifer becomes bigger the future matters less, because the effects of dropping water tables are pushed into the future, which is highly discounted. This is the reason for the convergence between free-market and social-planner solutions for large aquifers.

This result is the so-called Gisser-Sanchéz effect, or in the words of Gisser and Sánchez "…[regulation] of groundwater would not enhance the welfare of farmers compared with a strategy of free markets." There are no reasons to believe that policies

[3] See Gisser and Sánchez (1980a) and Esteban (2010) for details.

regulating large aquifers would achieve any welfare gains. Furthermore, policy implementation involves transaction costs that should be accounted for, and the transaction costs make the dismissal of any groundwater policies even stronger.

The model of Gisser-Sánchez just described is now extended to include environmental damages. In the context of large-scale intensive pressures on water resources in arid and semiarid regions worldwide described in section 1, vast numbers of agents are extracting more water from aquifers than actual recharge, depleting the water storage and damaging the associated ecosystems.

Table 1. Solution equations for the water table H and the water extractions W

Solutions under free market
$H(t) = \frac{-(\alpha-1)(g+kC_0)-R}{(\alpha-1)kC_1} + \left[\frac{R+(\alpha-1)(g+kC_0)+[(\alpha-1)kC_1]H_0}{(\alpha-1)kC_1}\right]e^{\frac{tkC_1(\alpha-1)}{AS}}$ (1)
$W(t) = \frac{-R}{(\alpha-1)} + \left[\frac{R}{(\alpha-1)} + g + kC_0 + kC_1H_0\right]e^{\frac{tkC_1(\alpha-1)}{AS}}$ (2)
Solutions under regulation with the extraction cost externality
$H(t) = \frac{-(\alpha-1)(g+kC_0)-R}{(\alpha-1)kC_1} + \frac{R}{rAS} + \left[\frac{(\alpha-1)(g+kC_0)+[(\alpha-1)kC_1]H_0+R}{(\alpha-1)kC_1} - \frac{R}{rAS}\right.$ (4)
$W(t) = \frac{-R}{(\alpha-1)} + \left[\frac{R}{(\alpha-1)} + g + kC_0 + kC_1H_0 - \frac{kC_1R}{rAS}\right]e^{tx_2}$ (5)
Solutions under regulation with the extraction cost and environmental externalities
$H(t) = \frac{-(\alpha-1)(g+kC_0+kC_1H_0-\beta(\alpha-1)k)-R}{(\alpha-1)kC_1} + \left[\frac{(\alpha-1)(g+kC_0+kC_1H_0-\beta(\alpha\right.$ (7)
$W(t) = -\frac{R}{(\alpha-1)} + \left[\frac{R}{(\alpha-1)} + g + kC_0 + kC_1H_0 - \beta(\alpha-1)k - \frac{kC_1R}{rAS}\right]e^{tx_2}$ (8)

The analytical demonstration that policies and social interventions for sustainable aquifer management could make sense is based on an enlarged model that includes damages to ecosystems dependent on the aquifer. These environmental damages are social costs but they are external to markets and, thus, they are not taken into account by farmers in their decisions on water extractions. The extended model is an optimal control problem that includes the two types of externalities that appear in exploiting aquifers: the water extraction cost and the environmental externalities.

The ecosystem damages from groundwater depletion in large aquifer systems are driven by complex underlying biophysical processes that include nonlinear, dynamic, spatial and threshold features. The specification of the damage cost function can be difficult because of the lack of knowledge and data collection on these processes.

Another problem is that ecosystems may undergo abrupt shifts between alternative states, called “regime shifts” (Scheffer et al., 2001). Ecosystems may respond smoothly to gradual changes in groundwater depletion, but responses can be strong beyond certain thresholds, leading to dramatic transitions or even to the collapse of linked ecosystems. In such cases, the restoration of the previous groundwater stock is not sufficient for the recovery of the previous state of ecosystems (hysteresis). Given the limited knowledge and information available on ecosystem damages from depletion in large-scale aquifer systems, simplifying assumptions seem reasonable, and the damage cost function has been specified as linear in the volume of depletion.

Social welfare is defined by the farmers’ revenue minus the cost of water extractions and the cost of ecosystem damages (Esteban and Albiac, 2010a). The formulation of the optimal control problem is given by:

$$Max \int_0^\infty e^{-rt}\left[\frac{1}{2k}W_t^2 - \frac{g}{k}W_t - (C_0 - C_1 H_t)W_t - \beta[-(\alpha-1)W_t - R]\right]dt$$

$$s.t.\ \dot{H} = \frac{R + (\alpha - 1)W_t}{AS}, \qquad H(0) = H_0 \qquad (6)$$

where farmers’ revenue is $\frac{1}{2k}W_t^2 - \frac{g}{k}W_t$, the cost of pumping is $(C_0 + C_1 H_t)W_t$, and the new component is $\beta[-(\alpha-1)W_t - R]$, the cost of environmental damages. This environmental cost is defined as the volume depleted from the aquifer in each period $-(\alpha-1)W_t - R$ multiplied by parameter β. Aquifer depletion is the difference between net extractions $(1-\alpha)W_t$ and recharge R. Parameter β is the cost of damages to ecosystems from each cubic meter of aquifer depletion.

Solving the optimal control problem, the solution equations for the water table and the water extractions are given by equations (7) and (8) in Table 1. These solution equations under policy regulation (7) and (8) are different from those of Gisser and Sánchez (4) and (5), because of the additional terms involving the ecosystem damages of parameter β . Equations (7) and (8) prove analytically that the introduction of ecosystem damages results in a different behavior of the aquifer under free-market and policy regimes, with quite different social welfare outcomes.[4]

This result is no surprise because if extractions are penalized for some other reason than the extraction cost externality, namely ecosystem damages, then extractions are further reduced. For large aquifer systems supporting important environmental assets, there are two countervailing effects on welfare. One is the extraction cost externality, with welfare effects from depletion pushed into the future and being heavily discounted for large aquifers, making the Gisser-Sánchez effect possible. The other is the environmental externality that increases the welfare difference between policy and free-market regimes all along the planning period. Therefore, the validity of the Gisser-Sánchez effect is largely an empirical question, which is examined in the following section.

3. Empirical Application to the Western and Eastern La Mancha Aquifers

The Western and the Eastern La Mancha aquifers and the adjacent wetlands are located in Castilla-La Mancha, in Southern Spain. The development of intensive use of groundwater for agriculture in recent decades has caused significant damages to aquatic ecosystems and also to human uses downstream because of aquifers depletion and reduction of river flows in La Mancha. Eighty kilometers of the Upper Guadiana River have disappeared, together with important associated wetland systems supporting very rich aquatic ecosystems and migrant waterfowl.

These two large aquifers are contrasting examples of management regimes. The interest in the case stems from the fact that the Eastern La Mancha aquifer is unique in that it is a large aquifer being managed towards sustainability, due to the success of the

[4] The reason is that equations (7) and (8) of the policy regulation regime cannot be simplified to equations (1) and (2) of the free-market regime even when AS is large, because equations (7) and (8) have additional β terms in the right hand side of $H(t)$ and $W(t)$. In $H(t)$, β appears in the first term and in the parenthesis, while in $W(t)$, β appears in the parenthesis. Since these additional environmental terms β do not vanish, the equations are different from the free-market regime.

collective action engaged by stakeholders (Esteban and Albiac, 2010b). In stark contrast, its neighboring Western La Mancha aquifer is being grossly mismanaged.

The expansion of irrigation in the Eastern La Mancha aquifer during recent decades caused a substantial decline in the aquifer's water table. The institutional developments started when farmers became aware of the problems from aquifer depletion and responded by creating the water-user association in 1995, aimed to jointly manage the aquifer. The process began because the town of Albacete wanted a concession of water for urban use from the basin authority, and the basin authority with the support of the downstream stakeholders in Valencia State, called for the control of extractions and threatened farmers by not issuing water rights. Other reasons that facilitated active support from farmers were the increase in pumping costs because of the fall of the aquifer water table, and the relatively small number of farmers involved.

The key for this system to work is that farmers themselves are involved in the process of enforcement and control. The efforts of the water-user association, together with the support of the basins authority and the state government, have resulted in a reduction in extractions during the 2000s.

The accumulated depletion in the Western La Mancha aquifer was already 1.50 km^3 in 1987, and the response by the basin authority to this rapid degradation was to declare the aquifer "officially" overdrafted, so that the construction of any new wells was forbidden. However, it took four years for the basin authority to design the management regime to curb extractions by a system of water quotas assignment. This management regime was completely ignored by farmers, and the basin authority was unable to enforce it, both because of lack of resources and lack of political will. A lobby to support illegal pumping was created by farmers' unions, municipalities, water-user associations and members of the state government.

Large amounts of money were spent in Western La Mancha during the 1990s to pay farmers in exchange for water extractions abatement, without any success (CES, 2006).[5] In 2005, the basin authority brought to court 5,000 illegal wells, but then the federal ministry of environment fired the president and the water commissioner of the basin authority, yielding to pressures from farmers and the state government. The current policy in the Western La Mancha aquifer is the Special Plan of the Upper Guadiana to

[5] This is the "Wetlands Plan" of 1992-2002 financed with European Union funds, with payments amounting to 250 million Euros, while depletion increased from 1.80 to 3.10 km^3 along with illegal pumping (Iglesias, 2002).

recover the aquifer, with huge investments of 5.5 billion Euros in buying water rights, afforestation, rural development, urban supply and wastewater treatment (CHGN, 2008). But this seems to be a misguided policy to recover the aquifer, because stakeholders' cooperation requires serious commitments to manage and care for the aquifer, and cannot be exclusively bribed for by side payments.

Undoubtedly, it is better for aquifers if farmers cooperate than if they don't. But how exactly cooperation can be brought about in either normal or difficult circumstances is a tough question. There are no easy recipes, as shown by the pervasive mismanagement of aquifer systems in arid and semiarid regions around the world. In the La Mancha case, several factors contributed to the emergence of cooperation in Eastern La Mancha. One was the significant increase in pumping costs due to the alarming fall in the water table of up to 80 meters in some locations (Sanz et al., 2009). Another factor was the credible threat of forbidding extractions, which came from the Jucar basin authority, with the full support of downstream Jucar users with historical water rights that date back centuries. Also, the number of farmers was only 1,000, much smaller than the number of farmers (around 70,000) in Western La Mancha (Esteban and Albiac, 2010b).

The extended model is applied to the Eastern and Western La Mancha aquifers. The purpose is to confirm empirically the analytical finding of the previous section, namely that regulation policies can improve substantially the management of aquifers. The procedure followed is to compare the current management of the Eastern and Western

Table 2. Parameters of the Western and Eastern La Mancha aquifers

Parameter	Western La Mancha	Eastern La Mancha
Quasi-rent of cereals (b_c)	628 (€/ha)	542 (€/ha)
Quasi-rent of vegetables (b_v)	3,500 (€/ha)	4,900 (€/ha)
Quasi-rent of fruit-trees (b_f)	1,200 (€/ha)	1,280 (€/ha)
Water use by cereals (w_c)	4,340 (m^3/ha)	5,860 (m^3/ha)
Water use by vegetables (w_v)	4,020 (m^3/ha)	4,920 (m^3/ha)
Water use by fruit trees (w_f)	3,150 (m^3/ha)	3,150 (m^3/ha)
Pumping cost intercept (C'_{0i})	0.08-0.11 (€/m^3·ha)	0.06-0.11 (€/m^3·ha)
Pumping cost coefficient (C'_1)	0.0004 (€/m·m^3·ha)	0.0004 (€/m·m^3·ha)
Return flow coefficient (α)	0.2	0.2
Social discount rate (r)	0.05	0.05
Water table current elevation (H_0)	640 (m.a.s.l.)	660 (m.a.s.l.)
Recharge (w/o return flows, R)	0.36 (km^3)	0.25 (km^3)
Area of the aquifer (A)	5,500 (km^2)	7,260 (km^2)
Storativity coefficient (S)	0.023	0.034
Elevation of the aquifer surface (S_L)	665 (m.a.s.l.)	690 (m.a.s.l.)

Environmental damage of depletion (β)	0.05 (€/m^3)	0.05 (€/m^3)

Source: Esteban and Albiac (2010b). The reference year for the parameter values is 2007.

La Mancha aquifers, with three alternative management regimes. These three regimes are free-market, partial-cooperation and full-cooperation regimes.

The free-market or no-cooperation regime is characterized by myopic pumping by agents that disregard the extraction cost and the environmental externalities, leading to depletion of the aquifer. The second regime is partial cooperation by agents that account only for the extraction cost externality. The third regime is full cooperation by agents that account for both the extraction cost and the environmental externality.

Myopic pumping is characterized by agents that maximize just the current period private profits, without considering externalities. When agents account for the extraction cost externality, they maximize the value of their future stream of collective private profits. Finally, when agents account for both externalities, they maximize social welfare, because both the value of collective private profits and the environmental damages are internalized in their extraction decisions.

The classification of the current aquifer management in one of the three regimes is done by comparing the pattern through time of the variables water table level and water extractions. The assumption is that the current management in La Mancha aquifers is a consequence of the choice made by agents on the type of regime, from no cooperation in dealing with any externality to full cooperation to internalize both externalities.

There are three farming production activities in the model: cereals, vegetables and fruit trees. These crop activities are irrigated and require a fixed amount of water, and therefore the water extractions from the aquifer are driven by the irrigated acreage. The

Table 3. Results of management regimes in the Western La Mancha aquifer

	Initial Period	No Cooperation or Free Market Collapse in year 12	Partial Cooperation Extraction cost externality	Full Cooperation Extraction cost & environmental externalities
Water table (m.a.s.l.) (natural level=665)	640	608	649	661
Gross extractions (km^3)	0.59	1.00	0.44	0.44
Water stock (km^3) (natural stock=6.50)	3.50	0	4.50	6.00
Acreage (ha)	191,400	253,400	120,700	120,700
Time to stationary (years)	-	12	13	19
Welfare (M€, 30 y. period)	-	430	1500	1790

Source: Esteban and Albiac (2010b).

hydrologic and economic parameters used to run the model simulations are shown in Table 2.[6] The information to build the model includes crop acreage by municipal district (Gobierno de Castilla-La Mancha, 2008), costs and revenues by crop in the region (MARM, 2008) and biophysical information (Martínez-Santos et al., 2008; Sanz et al., 2009). The cost of damages to ecosystems from each cubic meter of aquifer depletion (parameter β) has been estimated based on the contingent valuation study by Júdez et al. (2000, 2002).[7] The GAMS package has been used for data management and scenario simulation.

3.1. Results from the management regimes

The results from the management regimes in the Western and Eastern La Mancha aquifers are presented in Tables 3 and 4. The free-market regime in Western La Mancha expands acreage while social welfare is plummeting, with gross extractions growing from 0.59 km^3 to 1.00 km^3. Current welfare falls by three quarters, and finally irrigation

Table 4. Results of management regimes in the Eastern La Mancha aquifer

	Initial Period	No Cooperation or Free Market	Partial Cooperation Extraction cost externality	Full Cooperation Extraction cost & environmental externalities
Water table (m.a.s.l.) (natural level=690)	660	627	679	689
Gross extractions (km^3)	0.42	0.31	0.31	0.31
Water stock (km^3) (natural stock=10.00)	7.00	3.90	9.00	9.80
Acreage (ha)	90,300	73,500	59,100	59,100
Time to stationary (years)	-	14	17	22
Welfare (M€, 30 y. period)	-	810	1150	1280

[6] The variables and parameters of the empirical model are slightly different from the analytical model. For example, the water input demand is not continuous but formed by three rectangles corresponding to the (shadow) water prices and water used by vegetables, fruit-trees and cereals. For each of these crops, net income is equal to net income per cubic meter (p) multiplied by the water used in producing the crop (v). The water used in producing the crop (v) is equal to crop acreage (ha) multiplied by the crop water requirement per hectare (w), so net income of a crop is equal to $p \cdot w \cdot ha$. Defining the crop net income per hectare b , as the net income per cubic meter multiplied by the crop water requirement, or $b = p \cdot w$, the net income of a crop is then $b \cdot ha$, and total net income from the three crops is given by $b_c \cdot ha_c + b_v \cdot ha_v + b_f \cdot ha_f$. Detailed information on the empirical model specification, variables and parameters can be found in Esteban and Albiac (2010b).

[7] Parameter β is only an approximation to ecosystem damages, because the information on ecosystem damages from depletion is quite limited. The value of β has been calculated as the value of ecosystems supported by the aquifer (based on the contingent valuation study), divided by the water storage of the aquifer. Since this is a crude approximation to ecosystem damages, a sensitivity analysis has been performed for different values of parameter β, the cost of damages to ecosystems. Aquifer depletion is inversely related with damages; it is lower when damages are high (large β) and higher when damages are low (small β). See details on the sensitivity analysis in Esteban and Albiac (2010b).

Source: Esteban and Albiac (2010b).

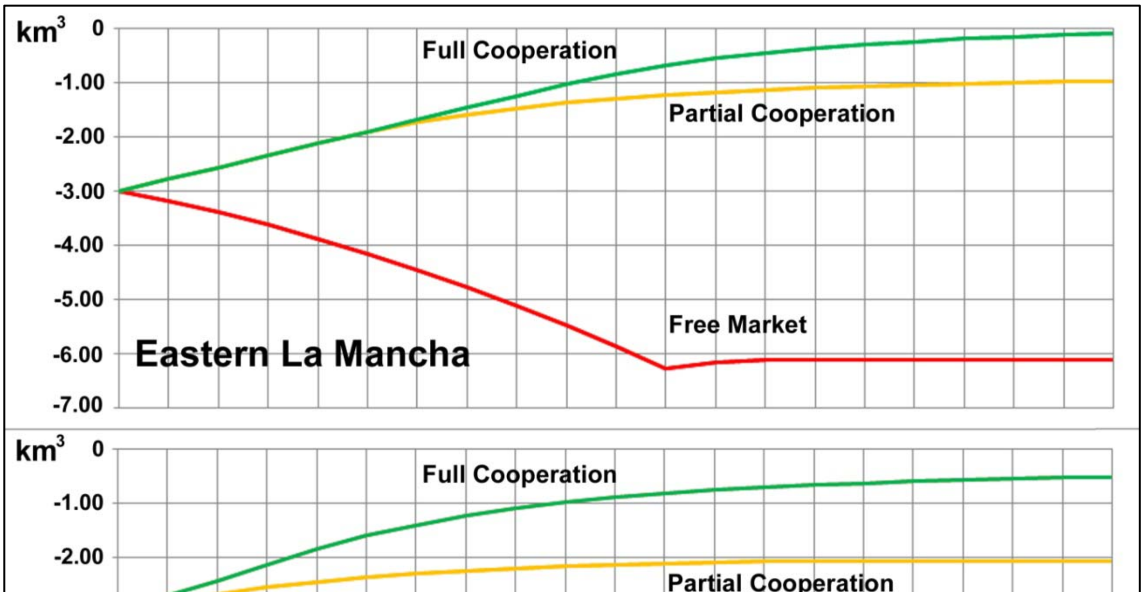
collapses because depletion above 6.00 km^3 prevents any further extractions. The collapse of the aquifer would be tied to important quality problems in the remaining stock of water, which hamper the subsequent gradual recuperation of the aquifer.

The free-market regime in Eastern La Mancha expands also current acreage with a massive depletion of 6.30 km^3, and current welfare is reduced by half. Rising pumping costs will reduce irrigation, and thus aquifer storage recovers somewhat. The Eastern La Mancha aquifer does not collapse under the peak depletion of 6.30 km^3 because storage is above 10.00 km^3, much larger than the Western La Mancha storage.

Partial cooperation brings down extractions in both Western and Eastern aquifers, with a recovery of storage above 1.00 km^3. However, the rise in the water table is not enough to recover all the "tablas" systems and 80 kilometers of the dried-up Guadiana River. Full cooperation is needed for recovery of both aquifers, requiring that farmers incorporate not only the extraction cost externality, but also the environmental externality. Under full cooperation, farmers curb extractions by more than half during several years in both aquifers, yielding a relatively rapid recovery of the water table and the highest social welfare (Figure 1).

The present value of welfare for a planning period of thirty years shows large differences between free market and cooperation, either partial or full (Tables 3 and 4). In Western La Mancha welfare gains are very large, from 430 million Euros under free market up to 1,500 and 1,790 million Euros under partial and full cooperation, respectively. In Eastern La Mancha welfare gains are also substantial, from 810 million Euros under free market up to 1,150 and 1,280 million Euros under partial and full cooperation, respectively. These empirical results show that the difference between free

Figure 1. Aquifers depletion under free market, partial and full cooperation (km^3)



Source: Esteban and Albiac (2010b).

market and partial cooperation is very significant, so that the GSE would not hold even before environmental externalities are taken into account by full cooperation.

3.2. Comparison with the current management

The comparison between the simulations of the three management regimes and the current management indicates the degree of competition or cooperation among farmers in each aquifer. The accumulated depletion in both aquifers is nearly 3.00 km^3 and has followed a similar pattern between 1980 and 2000; however, during the last decade the data show success in the efforts made in Eastern La Mancha to curb extractions and eliminate overdraft (Table 5). The overdraft in Eastern La Mancha at the end of the 1990s was 0.10 Mm^3 per year, resulting from annual extractions around 0.43 km^3 and recharges of 0.33 km^3. After establishment of formal cooperation in Eastern La Mancha starting in 2000, annual extractions have been falling steadily during the following decade from 0.40 km^3 down to 0.30 km^3 in recent years, with the average of 0.35 km^3 being quite close to the safe recharge. The depletion trend of 0.10 km^3 per year of

Table 5. Extractions in Eastern and Western La Mancha during the last decade

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Extractions, Eastern La Mancha (km^3)	0.42	0.39	0.38	0.37	0.37	0.38	0.35	0.29	0.27	0.30
Extractions, Western La Mancha (km^3)	0.59	0.61	0.68	0.65	0.62	0.43	0.67	0.61	0.44	0.49

Source: Sanz el al. (2009), IGME (2009) and CHJ (2009).

previous decades has fallen to 0.03 Mm^3 per year during the last decade. This achievement derives from the collective action of farmers.[8]

The overdraft in Western La Mancha at the end of the 1990s was 0.11 km^3, resulting from extractions around 0.58 km^3 and recharges around 0.47 Mm^3. But this overdraft has been unabated in Western La Mancha during the last decade, as the evidence from Table 5 shows. All extractions are above recharge except for two years, and the average extractions during the decade are 0.58 km^3, well above recharge.

The current regime in Western La Mancha aquifer is far from any cooperation, partial or full, and the aquifer is being largely overdrafted. The current management in Western La Mancha is certainly free market, and the case is troubling because there is no sign indicating that farmers are willing to cooperate. The huge multibillion investments of the Special Plan of the Upper Guadiana (CHGN, 2008) are unlikely to induce cooperation. Curbing the water extractions in Western La Mancha is quite a challenge at present because of the past history of policy mistakes and stakeholders opposition. In any case, failure to implement the right policy measures would lead to the collapse of the aquifer, with large economic and environmental losses.

The current regime in Eastern La Mancha is moving towards partial cooperation, a change from free market that has taken place during last decade. Cooperation in Eastern La Mancha started in the middle of the 1990s and, since then, the water table level has stabilized because farmers have managed to reduce extractions in the last ten years. Although water extractions have fallen below the sustainable aquifer recharge (0.31 km^3) by the end of the 2000s, the recovery of the aquifer calls for larger reductions in extraction, down to 0.20 or even 0.10 km^3 before returning to the 0.31 km^3 level of sustainable recharge.

These empirical results show that farmers in Eastern La Mancha are moving towards internalizing the extractions costs but not the environmental costs. Therefore, further advances in cooperation or other alternative policy instruments are needed to curb extractions and recover the aquifer. A steep decline in initial extractions to accommodate environmental damages would be met by farmers' opposition, because their benefits would be reduced and not increased, as in the case of the extraction cost externality. Environmental externalities will either be internalized through the involvement of other stakeholders, even those farther from the aquifers, or will require

[8] Farmers have changed their cropping patterns by planting less water-demanding crops, switching from summer to winter crops, and planting only one crop per year instead of two crops.

additional policy interventions by the basin authority. Interventions could include extraction restrictions or economic instruments under the appropriate institutional setting to make them legitimate.

4. Conclusions

The mismanagement of groundwater resources is an important policy issue worldwide. In arid and semiarid regions around the world, there has been a huge increase in extractions from groundwater systems in recent decades. These pressures are generating important problems of scarcity and water-quality degradation in most basins of these regions. Aquifer depletion is a relevant policy issue not only because of the exhaustion of these water bodies for human uses, but also because of the important damages sustained by connected ecosystems.

Groundwater is a common pool resource characterized by rivalry in consumption and non-exclusion. Myopic individual pumping by agents disregards the extraction cost and environmental externalities, leading to excessive depletion of the aquifer and the degradation of linked ecosystems. In previous literature, the usual market failure that has been considered in aquifer management is the water extraction cost externality. This externality arises because extractions by each farmer reduce the aquifer stock and increase the pumping costs for all farmers and subsequent periods. But another important market failure is the damage produced by the fall in the water table on the ecosystems dependent on the aquifer. The theoretical and empirical analysis presented here indicates that environmental externalities may play an important role in the design of policies and regulations in the management of large aquifer systems.

Gisser and Sánchez recognized the market failure of the extraction cost externality, and proposed a theoretical model to analyze free-market and policy intervention. Under free market, farmers equate individual marginal costs of pumping with the marginal value of the physical product. Farmers know that there are economic and environmental externalities involved but, since the aquifer is a common pool resource, their rational response is a myopic management behavior, leading to the degradation and eventual destruction of aquifer systems. Therefore, without any policy regulation, farmers do not internalize the extraction costs and environmental externalities, causing the ensuing market failure. A suitable policy intervention should induce some form of cooperation or support by farmers in order to achieve any welfare gains.

Gisser and Sánchez compare social welfare under free-market and policy regulations. Their finding is the so-called Gisser-Sánchez effect; the enhancement of social welfare from regulation does not justify any policy action to correct the market failure. We postulate that even when considering large aquifer systems, which is the main assumption for the GSE to hold, the ecosystem damages from depletion cannot be ignored. If they are important, the correction of the market failure increases social welfare, and this welfare difference between free-market and policy regimes is driven by the size of the ecosystem damages.

For large aquifer systems in arid and semiarid regions worldwide, the vast aquifer depletion during recent decades is causing severe environmental damages. Therefore, our theoretical finding seems relevant and calls for a re-evaluation of current groundwater exploitation worldwide, in order to design workable policies for protecting human activities and ecosystems that depend on healthy aquifer systems.

The empirical analysis focuses on two large aquifers in Spain: the Western and Eastern La Mancha aquifers. These aquifers are located in the Southern Iberian Peninsula, an area experiencing in recent decades strong pressures from the development of irrigation agriculture. An important empirical result is that both the extraction cost and the environmental externalities have sizable welfare effects. In particular, the extraction cost externality involves the main welfare effect in the two aquifers, contradicting the Gisser-Sánchez effect.

The empirical findings show that the current management regime in Western La Mancha is close to free market, and the aquifer may collapse in the coming decades. The current management in the Eastern La Mancha aquifer is advancing from free market towards full cooperation. Farmers started worrying about collective management in the middle 1990s, and by the year 2000 formal cooperation among farmers was up and running. Since then, extractions have been falling significantly from 0.40 to 0.30 km^3 and are now below recharge. We think that this is an important accomplishment, which may be relevant for other large aquifers worldwide. Eventually, some lessons learned from this experience could contribute to the improvement of the pervasive mismanagement of aquifer systems across the globe.

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