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Comparing Alternative Policies for Modification of Energy Subsidies: The Case of Groundwater Pumping for Irrigation

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ABSTRACT

The present paper studies the effects of alternative modifications of a subsidy for electricity used to pump groundwater on the behavior of profit maximizing groundwater users. It proposes a stylized model for groundwater extraction, and then numerically derives general results by simulation. The model is applied to aquifers in Leon, Guanajuato, Mexico and Kern County, California. The performance of two traditional policy intervention measures—subsidy elimination and reduction—are compared to a new, innovative modification policy, namely, decoupling the subsidy from the electricity bill; this policy is arguably more politically acceptable. The results of extensive simulations suggest that the rate of aquifer water extraction, and the consequent level of water in the aquifer, can be improved significantly by changing the subsidy structure.

1. Introduction

Many countries regulate the consumption of scarce natural resources such as groundwater by providing their users with subsidies. Although some subsidies produce the desired effects of reducing consumption, others have perverse effects on the economy and the environment. Perverse subsidies for natural resources were estimated at one point to reach $1,450 billion dollars per year, and were held accountable for a $30 trillion distortion in damages (Myers, 1999). In the developing world, water subsidies accounted for $45 billion dollars of annual costs; meanwhile, agricultural subsidies (including irrigation subsidies) reached $65 billion dollars in developing countries and up to $335 billion dollars in developed countries (Pearce, 2003).

Electricity subsidies for pumping groundwater present a major challenge for groundwater regulators around the world. For example, Mexico, India, and Pakistan have implemented subsidies for electricity used to pump groundwater in an effort to render the agricultural sector more competitive. This issue is socially crucial because the number of people depending on groundwater is significant; in India, 55–60 percent of the population relies on groundwater mainly for agricultural production (Mukherji and Shah, 2005). In India, the electricity subsidy is leveraged frequently as a political tool with some regions, such as Punjab, taking the extreme approach of not charging for electricity used for pumping groundwater at all (Jain, 2006; Shah et al., 2006).

In Mexico, a total volume of 29.5 km^3 is extracted annually from groundwater sources. Of this amount, 70% is used in irrigated agriculture. The Mexican government decided in the early 1990s to provide a subsidy for electricity used for pumping groundwater for irrigation. The subsidy—Tarifa 09—is volumetric; it is provided to farmers on the basis of the amount of electricity they consume in pumping the groundwater. As a result of the subsidized pumping cost and other policies, 101 of the 188 major aquifers in Mexico have been overdrafted due to mismanagement practices and lack of incentives for using appropriate irrigation technologies (Muñoz et al., 2006).

According to the Mexican National Water Law, water used for irrigation is not priced. Rather, farmers are required to pay only for the costs of extracting water (either from surface or groundwater sources). These incentives for farmers hide the real costs of pumping, which go beyond the direct cost of the subsidy. The current institutional framework in Mexico leads to inefficient exploitation of groundwater resources and negative externalities (Asad and Dinar, 2006; Dinar et al. 2008).

2. Previous work

There is a large body of literature concerning groundwater

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extraction and electricity subsidies. Most of this literature focuses on the inefficiencies of water allocation due to misleading price signaling to the farmers. Shah et al. (2006) analyzed the groundwater irrigation economy in South Asia using a survey given to groundwater users in India, Pakistan, Nepal, and Bangladesh. Their findings suggest that the over-extraction of groundwater resources has been shaped by South Asia's energy pricing. They report that the subsidy is regressive because prosperous landowners predominately have electric pumps, whereas underserved farmers either choose diesel pumps or purchase water from their wealthier neighbors.

Shah et al. (2008) have demonstrated how electricity policy regulates water pumping from aquifers in Gujarat State, India. Dubash (2007) has analyzed the inherent relationship between electricity and groundwater by assessing the effect of subsidies on groundwater consumption, using the case of India as an example. His findings coincide with those of Shah et al. (2006) regarding the regressive nature of the subsidies for electricity. Dubash (2007) also assessed the impact of this subsidy on the quality of the electricity service provided by the State Electricity Board of India. He reports that farmers prefer to continue receiving the subsidy even if it means low-quality service. Discussing the institutional arrangements and policies related to groundwater in India, Pakistan, Bangladesh, China, Mexico, and Spain, Mukherji and Shah (2005) have concluded that despite the wide range of institutional setting across these countries, the understanding of the social and economic impact of groundwater is still lacking, and the scientific study on groundwater is biased toward the resource and its development rather than to its management and the externalities created by its use.

The groundwater literature also focuses on the implications of regulatory policies. Gisser and Sanchez (1980) analyzed the benefits of command and control versus market allocation of groundwater. They presented a dynamic model that maximizes the value of the net benefit, and concluded that the changes in welfare associated with the impact of central regulations (such as pricing and quotas) on groundwater are negligible. Feinerman and Knapp (1983), who analyzed groundwater allocation using a similar dynamic model and applied it to the Kern County aquifer in California, supported the conclusions of Gisser and Sanchez (1980). Their results suggest that the social benefits of implementing command and control mechanisms (e.g., pumping quotas) are small compared to the status quo benefits (Feinerman and Knapp, 1983, p. 709), and therefore may not justify the additional transaction costs of the regulation. On the other hand, building on principles in the Feinerman and Knapp's approach, Esteban and Albiac (2011, 2012) modeled the Eastern and Western La Mancha aquifers, and concluded that, when taking into account the environmental damage caused by over-drafting groundwater resources, the social benefits from a command and control policy are sizable.

Burness and Brill (2001) discussed the role of policy in the case of farmers who are allowed to switch technologies. The authors found that regulation can lead farmers to switch to more efficient technology because the future costs of pumping become more explicit. On the other hand, Kim et al. (1989) discussed ways that farmers adapt their behavior, particularly via crop choices, when the price of extracting groundwater increases. Their findings suggest that under social optimum behavior farmers move away from water-intensive crops (sorghum) twice as much as they do while displaying common property behavior, thereby increasing the efficiency of groundwater use.

Although the literature on the impact of energy costs on groundwater management sheds light on the complex conundrum of the relationship between these commodities, more research is needed to analyze alternative policy options for addressing energy subsidies, which could help addressing the groundwater overexploitation problem.

More directly related to our study, Muñoz et al. (2006) proposed different procedures for modifying the electricity subsidy and reducing water extractions to a level that could help stabilizing the over-drafted aquifers. These measures include two traditional interventions—elimination and reduction of the subsidy—and the decoupling of the subsidy from the electricity price, which rewards farmers a cash transfer in the amount of the subsidy. Decoupling can be implemented by using several methods, including:

- Grandfathering: The transferred sum is equivalent to the average consumption of electricity in the last i years (Muñoz et al., 2006, used $i = 3$).
- Land surface: The transferred sum is based on the amount of irrigated land.
- Egalitarian: The transferred sum is based on dividing equally the grand total of the subsidy among all farmers.

Each of these alternative mechanisms (or reforms) helps addressing the problem, but also has the potential of creating its own difficulty. Grandfathering is similar to the status quo, as it might create an incentive to draw even more groundwater than before in order to receive a higher financial transfer. The surface-based decoupling policy might promote an increase in the irrigated area, and the egalitarian method might help resolving the concentration of the subsidy while harming big producers.

We note that, in addition, the political economy of the subsidy modification ought to be addressed. In countries such as Mexico, the agricultural sector is overrepresented and decisions to remove subsidies are unpopular among politicians because of their negative electoral consequences.

Our study proposes a model that focuses on potential changes in farmer behavior due to changes in the subsidy mechanism (i.e., *elimination*, *decoupling*, and *reduction*). We propose a dynamic optimization model for analyzing the changes in groundwater extraction under these mechanisms. The model is applied to data from Leon, State of Guanajuato, Mexico and then extended in a robustness check to data from Kern County to evaluate the effectiveness of the three policy interventions described above under optimal extraction behavior and common property behavior of the users.

3. A dynamic model of groundwater extraction

We propose a dynamic model based on principles discussed in Gisser and Sanchez (1980), Feinerman and Knapp (1983), Esteban and Albiac (2011), Brozovic et al. (2006), and Nasim and Helfand (2015). Unlike the previous models, our model introduces electricity subsidy as part of the pumping cost function, and then implements various subsidy modification policies to simulate the alternatives under consideration. Building on an existing groundwater model framework, we contribute to the literature by introducing and studying the effects of two traditional policy intervention measures, namely, electricity subsidy elimination and reduction, and a third modification policy mechanism, namely, decoupling the subsidy from the electricity bill.

The model makes the simplifying assumption that the groundwater users are homogenous, and that all employ electric pumps for the extraction of groundwater.

3.1. Water demand

The water inverse demand function is represented by:

where W is the total demand for water, P is the full price for water, and g and k ($g \geq 0; k \leq 0$) are the intercept and price coefficients of the linear inverse demand function, respectively. Integrating the demand function from zero to q (quantity of surface and groundwater), we obtain the revenue function:

$$B(q) = gq - \frac{1}{2}kq^2 \tag{1}$$

where we define

$q \equiv (1 - \beta_{sw})q_{sw} + w.$

In the latter equation, q is the total water consumption that includes surface water allocations and groundwater withdrawals. Surface water allocations, denoted by $q_{sw,}$ are considered constant and exogenous. The parameter β_{sw} ($0 \leq \beta_{sw} \leq 1$)is the share of surface water that is lost in conveyance from the diversion point to the field but infiltrates into the aquifer. Our control variable is the amount of groundwater consumed, w. It is assumed that the water pumped from the ground is used in-situ, and that it does not suffer from cannel losses.

3.2. Extraction costs

Extraction costs are represented by:

$$C_t = C_0 + C_1(\gamma, x_t, \xi, w_t) \tag{2}$$

where

In Eq. (2), $\bar{X}$ is the distance of the land surface (in Mexico), or the distance of the sea level (in California) from the bottom of the aquifer. The term C_t denotes the total cost of pumping w units of groundwater at time t, where C_0 is the fixed cost, C_1 is variable cost that is a function of the water table depth ($\bar{X} - x_t$), which is also the pumping lift; it is measured as the distance between the land surface level (or the sea level) and the water table. ξ, is the cost of electricity required to lift a unit volume of water for a vertical distance (see Tables A1 and A2 in the Appendix for units and values in Mexico and California). The parameter γ ($0 \leq \gamma \leq 1$) is the level of the electricity price subsidy, with 0 meaning full subsidy and 1 meaning no subsidy.

The constrained maximization problem for the entire aquifer is as follows:

$$\max_{w_t} \sum_{t=1}^{\infty} \alpha^t \left\{ g q_t - \frac{1}{2} k q_t^2 - C_0 - [\gamma \xi (\bar{X} - x_t) w_t] \right\} \tag{3}$$

s. t.

$$x_{t+1} = x_t + \frac{\beta_{sw} q_{sw} + \beta_{dp}((1 - \beta_{sw})q_{sw} + w) + R - w}{AS},$$

$$0 \leq w \leq ASx_t,$$

$$0 < x_t \leq \bar{X},$$

where R is the recharge (e.g., precipitation), β_{dp} is the deep percolation rate (the amount of water that is returned to the aquifer after irrigation), A is the area of the aquifer, S is the specific yield, α^t is the discount factor, where $\alpha = \frac{1}{1+r}$, and r is the discount rate.

All pumping lifts and vertical distances are measured with respect to the mean land surface level (Mexico) and to the sea level (in Kern County, California, as used in Feinerman and Knapp, 1983). For the sake of simplicity, the spatial effects of pumping are assumed to be constant, and the behavior of the aquifer is assumed to be that of a "bathtub". We acknowledge that there are implications to these assumptions once spatially explicit analysis is introduced as shown in Suter et al. (2012).

Both the common property and optimal behavior scenarios of groundwater users are investigated by using computer simulations for 200 periods. The level of subsidy γ is varied systematically to simulate different subsidy reduction/elimination policies. Decoupling of the subsidy is tested by charging the full price of electricity and transferring money to the users, which is equivalent to their mean electricity consumption in the previous i periods.

3.3. Common property extraction behavior results

Under common property (or competition) extraction behavior, users are assumed to have little to no incentive to take into consideration the future costs of pumping. This means that these myopic groundwater users pump only until their marginal benefit of pumping equals their marginal cost. The first order conditions for the optimization problem of the myopic user are:

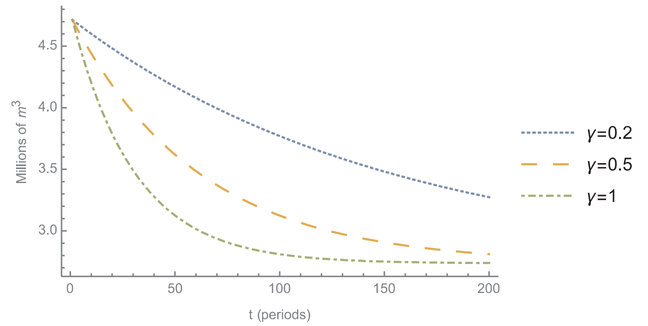

Fig. 1. Groundwater extractions under common property behavior.

$$g - k(w + q_{sw}(1 - \beta_{sw})) = \gamma \xi (\bar{X} - x_t) \tag{4}$$

A lower marginal extraction cost (or the effect of the subsidy level γ) will induce a larger quantity of water extraction at time t, excluding any future cost. Equation (4) demonstrates that the demand for groundwater may be derived using the common property condition:

$$w_t = \frac{1}{k}[g + kq_{sw}(\beta_{sw} - 1) + (x_t - \bar{X})\gamma\xi] \tag{5}$$

We proceed to present results of the simulations under common property for three conditions: status quo ($\gamma = 0.2$), reduction of the subsidy ($\gamma = 0.5$), and elimination of the subsidy ($\gamma = 1$). Below we present results (using coefficients in Appendix Table A1) for the level of extraction (Fig. 1) and for the water table depth in the aquifer (Fig. 2), using the parameter values of the aquifer in Leon, State of Guanajuato, Mexico.

Fig. 1 demonstrates clearly that once the subsidy is introduced, the distortion effect leads to a greater level of extraction from the aquifer. A lower steady state level was reached after 130 periods for $\gamma = 1$. No steady state was reached for $\gamma = 0.2$ and $\gamma = 0.5$within the 200 period horizon. Notice that since myopic users are optimizing by equating their marginal costs to their marginal benefits without accounting for the marginal user cost, they will start by extracting the same amount and then change their behavior as their cost changes over time. A similar result has been reported by Nasim and Helfand (2015) and Esteban and Dinar (2016).

The aforementioned statements become clearer when studying Fig. 2, where the collapse of the aquifer becomes more evident. The introduction of the subsidy results in the collapse of the aquifer, and the trend of the water table depth is slower and is kept at a higher level when there is no subsidy (i.e., $\gamma = 1$).

3.4. Optimal extraction behavior results

Under optimal behavior, users optimize their water extraction not

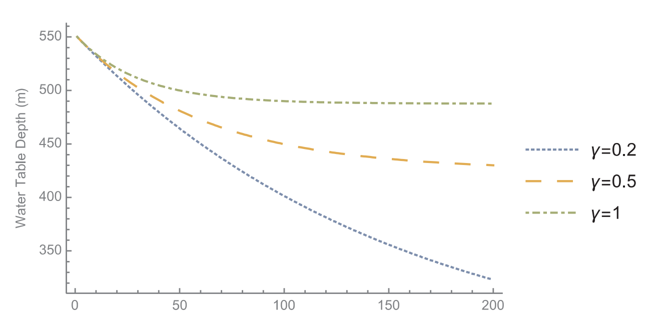

Fig. 2. Water table depth under common property extraction behavior.

only according to their marginal extraction cost, but also according to the marginal user cost (calculated as the reduction in the discounted future net benefits from a withdrawal of one additional unit in the current period (Feinerman and Knapp, 1983). Thus, the optimal extraction cost follows an optimal path that takes into account the present and future consequences of the extraction decision.

From the optimization problem in Eq. (3), we derive the Bellman equation:

$$V(x_t) = \max_{w_t}\left[gq_t - \frac{1}{2}kq_t^2 - C_0 - [\gamma\xi(X - x_t)w_t]\right] + \alpha V[x_{t+1}] \tag{6}$$

The Bellman equation simplifies the infinite horizon into a two-stage discounted function that helps computing the optimal path of extraction. From the Bellman equation we derive the first order conditions that yield the following Euler equation:

$$g - \gamma\xi(\bar{X} - x_t) - k((1-\beta_{sw})q_{sw} + w_t) = \alpha\frac{(\beta_{dp}-1)\left(\gamma\xi w_{t+1} - \frac{AS(g-\gamma\xi(\bar{X}-x_{t+1}) - k(1-\beta_{sw})q_{sw} + w_{t+1}))}{\beta_{dp}-1}\right)}{AS} \tag{7}$$

The Euler equation is used to derive the optimal path of extraction. It represents the marginal change of behavior by equating the marginal net benefits to the marginal costs in the present and in the discounted future (Parker, 2008). Raising the value of γ from 0.2 to 1 increases the present cost (represented by the left-hand side of the equation); however, it also increases the marginal, or discounted, benefit in the future (right-hand side of the equation). Therefore, modifications of the subsidy are anticipated to lead to deviation from the extraction path with subsidy, which will lead to a shallower, steady state of the water table.

From the Euler equation, we derive our policy rule that depends on the present and future values of the state variables. This implies that such a policy rule will optimize extraction according to the present cost of pumping water and the future discounted loss in net benefits from pumping an additional unit of water in the current period:

$$w_t = \alpha\frac{AS(\gamma\xi(x_t - \bar{X}) + kq_{sw}(\beta_{sw}-1) + 1)}{ASk} + \alpha\frac{(\beta_{dp}-1)\left(w_{t+1}\gamma\xi - \frac{AS(g+\gamma\xi(x_{t+1}-\bar{X}) - k(-\beta_{sw}q_{sw} + q_{sw} + w_{t+1}))}{\beta_{dp}^{-1}}\right)}{ASk}. \tag{8}$$

We have simulated the model under optimal extraction behavior for 200 periods using the three policy scenarios for subsidy reduction and elimination ($\gamma = 0.2$, $\gamma = 0.5$, and $\gamma = 1$), with parameters from Leon, Guanajuato (Appendix Table A1). We obtained the following results that are exhibited in Figs. 3 and 4.

Fig. 3 suggests that in the presence of the subsidy, the amount of water pumped is the highest, and no steady state is reached for the two cases of $\gamma = 0.2$ and 0.5. This result is consistent with the common property case. Fig. 3 also demonstrates that eliminating the subsidy induces reaching a steady state in the case of $\gamma = 1$ in earlier periods (around 90 years) compared to the common property behavior.

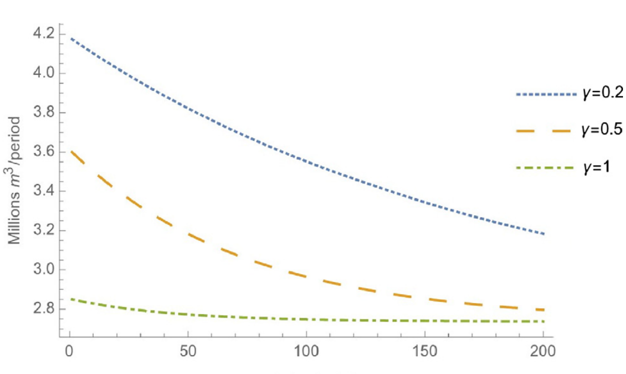

Fig. 3. Groundwater extraction under optimal behavior.

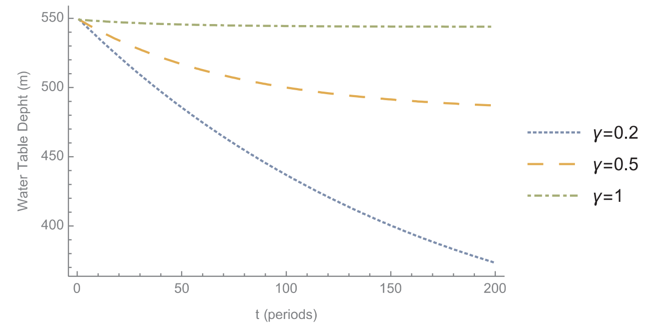

Fig. 4. Water table depth under optimal extraction behavior.

Fig. 4 confirms the aforementioned statement by showing that the water table depth converges almost immediately to a steady state in the case where the subsidy is eliminated; it reaches a steady state after 200 periods or so, with $\gamma = 0.5$, and it keeps a downward sloping trend when $\gamma = 0.2$. The water table depth is also the lowest when the subsidy is eliminated.

Decoupling the Electricity Subsidy

The analysis presented above includes two policy modifications aimed at addressing the distortions caused by the subsidy for electricity through reducing or eliminating the subsidy; these are demonstrated by the values $\gamma = 0.5$ and $\gamma = 1$, respectively. However, these two policies do not account for the political implications of the subsidy modification. Irrigation districts and farmers' unions comprise an influential political power with a strong lobby within the local and national governments of the countries that provide subsidies for energy irrigation. This political influence often hinders or completely destroys attempts at subsidy reduction. Decoupling the subsidy from the electricity rate and returning the equivalent sums to the users may eliminate the negative effect of the subsidy without resulting in the political cost associated with an explicit subsidy elimination (Muñoz et al., 2006). However, one has to consider equity concerns that may be detrimental to the decoupling policy as was discussed in the section Previous Work.

To analyze the impact of decoupling the electricity subsidy, the optimization problem must include the average cost of electricity incurred in the previous i periods.

The optimization problem with decoupling is provided below:

$$\max_{w_t}\sum_{t=1}^{\infty}\alpha^t\left\{gq_t - \frac{1}{2}kq_t^2 - C_0 - [\gamma\xi(X - x_t)w_t + \phi]\right\} \tag{9}$$

$s.\ t.$

$$x_{t+1} = x_t + \frac{\beta_{sw}q_{sw} + \beta_{dp}((1-\beta_{sw})q_{sw} + w) + R - w}{AS},$$

$$\phi = \frac{\sum_{k=\tau-i}^{\tau} w_k(\gamma\xi(X - x_t))}{i},$$

$$0 \le w \le ASx_t,$$

$$0 < x_t \le \bar{X},$$

where ϕ is the decoupling factor that ranges from $(\tau - i)$ to τ, with $\tau < \infty$ denoting a predetermined number of periods, and i is the number of periods that will be used to calculate the average electricity cost of pumping. At this stage, we start with the status quo, $\gamma = 0.8$. The decoupling factor is introduced as part of the profit optimization problem. Farmers do not have prior information on timing of implementation in order to avoid behavioral changes that could influence their level of payments.

This optimization problem can be divided into two stages for all values of t. In stage 1, where $t \leq \tau$, the Euler equation takes the form:

$$\frac{\gamma\xi(\bar{X}-x_t)}{i}-\gamma\xi(\bar{X}-x_t)+g-k((1-\beta_{dp})q_{sw}+w_t = -\alpha\frac{(\beta_{dp}-1)\left(\frac{\gamma\xi(i-1)(AS(\bar{X}-x_{t+1})+(\beta_{dp}-1)w_{t+1})}{(\beta_{dp}-1)i}\right)}{AS} \quad (10)$$

where we can compute w_t to obtain the corresponding groundwater demand:

$$w_t = \alpha\frac{AS\gamma\xi\bar{X}(1-i)+(\beta_{dp}-1)\left(\frac{\gamma(i-1)\xi(AS(\bar{X}-x_{t+1})+(\beta_{dp}-1)w_{t+1})}{(\beta_{dp}-1)i}\right)}{ASki} + \frac{AS(gi+\beta_{sw}ikq_{sw}-ikq_{sw}+\gamma\xi(ix_t-x_t))}{ASki} \quad (11)$$

The second stage of this optimization problem is for all $t > \tau$. Because ϕ is constant, the demand for groundwater is the same as under the optimal extraction behavior with elimination of the subsidy ($\gamma = 1$):

$$w_t = \alpha\frac{AS\{\gamma\xi(x_t-\bar{X})+kq_{sw}(\beta_{sw}-1)+1\}}{ASk} + \frac{(\beta_{dp}-1)\left(w_{t+1}\gamma\xi-\frac{AS[g+\gamma\xi(x_{t+1}-\bar{X})-k(-\beta_{sw}q_{sw}+q_{sw}+w_{t+1})]}{\beta_{dp}^{-1}}\right)}{ASk} \quad (12)$$

The model for decoupling was simulated for 200 periods, with the decoupling factor calculated separately for the preceding 3, 5, 10 and 15 periods. The choice of the numerical value of i was not arbitrary; the literature suggests using a three-period lag (Muñoz et al., 2006). For our simulations, we decided to study the effects of four different values because land use and subsequent water use can be affected drastically by short-term shocks both economic and environmental. Moreover, in semiarid climates as in Guanajuato and southern California, these shocks may result in unstable short-term land use. Therefore, using longer lags is advantageous when calculating the decoupling factor. The results of the simulations for subsidy elimination and for subsidy decoupling for $i = 15$ are exhibited in Fig. 5 for water table depth and annual net benefits.

Fig. 5 suggests that decoupling achieves similar results as elimination. However, a comparison of the annual net benefits of each method in Table 1 demonstrates that the total net present value of benefits under decoupling (for $i = 15$ years) is 241,488 million pesos over the 200 periods, whereas it is only 240,024 million pesos under elimination. The 0.6% difference is due to the fact that the cash transfer under decoupling enters as part of the benefit function but does not depend on the present water consumption.

Table 1 indicates the difference in net present value of benefits for $i = 3, 5, 10, 15$. The difference between these values is relatively small; it declines as i decreases, meaning that in the long-term the length of the period for the calculation of the decoupling factor has marginal impact on the user extraction decisions. However, there is an advantage in using longer lags for calculating the decoupling factor: with longer periods of time, the average pumping cost is affected less by exceptionally dry years, where the surface water supply could be affected, leading to higher water consumption that is not related to the subsidy. We use in our simulations a constant amount of surface water over the 200 year period for which we calculate the decoupling factor, while during longer periods surface water supply may vary. However, pumping decisions, as was well demonstrated by Koundouri (2004) and Shah et al. (2008), suggest that pumping costs (affected by electricity subsidy/rate) are the driving force behind the extraction decisions (see also discussion in the section Previous Work).

Table 1
Total net present value of net benefits.

Value of i (Years)	Net Present Value for 200 periods (Millions of Pesos)
3	240,354 (99.5)
5	240,548 (99.6)
10	241,025 (99.8)
15	241,488 (100.0)[a]

Note: The percentage values difference compared to $i = 15$ are shown in parentheses.

Dinar (2000) claims that water-pricing reforms may spark both support and opposition from various stakeholders, thereby highlighting the importance of compensation mechanisms for ameliorating the losses of the affected groups. In our study, the decoupling transfer acts as a compensation mechanism that reduces the political implications of the groundwater price reforms. This claim is supported by Muñoz et al. (2006), who argue that the decoupling mechanism can raise the overall level of farmers' utility by providing them the option of deciding how to allocate the subsidy money among the most efficient needs for themselves instead of constraining it to electricity consumption.

The decoupling policy seems viable, given the fewer controversial political economy implications of this policy intervention versus eliminating or reducing the subsidy. In addition, this policy modification provides the positive environmental implications of preserving the aquifer. Although this benefit is not the subject of this research, it warrants mentioning.

While our analysis focuses on Mexico, the political economy impact on the policy might vary depending on the country. For example, in the USA it might be the case that the public would object to a substantial direct payment transfer to farmers. However, as was indicated in Muñoz et al. (2006), the farming sector in Mexico is over-represented in the Mexican Congress and, therefore, direct payments may not be perceived as an infeasible policy.

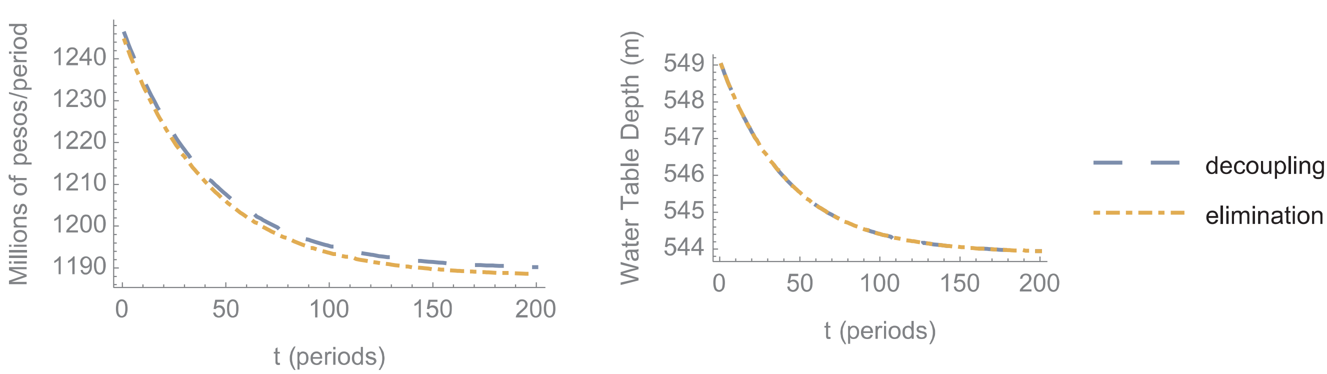

Fig. 5. Annual net benefits and water table depth under decoupling and elimination of subsidies.

3.5. Sensitivity analysis

We also have conducted a sensitivity analysis to assess the behavior of the dynamic model of demand when groundwater users are facing changes in the price of electricity (which represents the price of water extracted) by varying ξ from 1.8 to 2.8 thousand pesos per 1 million m^3/m. The results are displayed in Fig. 6. They show that the model behaves as expected: the water table depth (due to increased extractions) increases as the prices decrease, and the water extraction increases when the prices decrease. The annual net benefits decrease as ξ increases.

Deriving the electricity-price elasticity of extraction from the data in the upper panel of Fig. 6 suggests an inelastic value of 0.0904, which indicates that under the conditions in our simulations additional policy interventions (such as available know how and efficient irrigation technologies) may be needed to render the impact of price hike more effective. We refer to this point in the final section.

3.6. Robustness

We have repeated the simulations with data from another aquifer to assess the robustness of the results. For this purpose, we applied a set of parameter values from Feinerman and Knapp (1983) (see Appendix Table A2) to the aquifer in Kern County, California. Kern County has similar weather characteristics to the ones in the central region of Mexico, where the Leon aquifer is located. Both regions are semiarid, and both rely on groundwater supply for agriculture. However, some of the economic and geologic characteristics of these regions are different, as are some of the legal and institutional settings. We do not consider the differences in legal and institutional settings in these two regions. Figs. 7 and 8 display the results for the Kern county aquifer simulations.

The results (Fig. 7) of the common property extraction behavior simulation, which show the level of extraction and the water level in the aquifer, suggest that a steady state level of nearly 200 m below sea level was reached after 50 and 60 periods, respectively, for $\gamma = 0.2$ and 0.5, compared to a steady state that was reached after 200 periods for no subsidy ($\gamma = 1$). For the optimal behavior, the same steady state level was reached after 80 and 110 periods, respectively, for $\gamma = 0.2$ and 0.5, compared to no steady state within the 200 simulation periods for no subsidy ($\gamma = 1$). We note that the behavior of the water extraction curve over time in the Kern county aquifer for $\gamma = 0.2$ and 0.5 is less smooth then in the Leon aquifer, especially under the common property situation, although the ordinal results remain similar in both cases.

As for the water extractions with subsidy (Fig. 7), water extractions decline after 50 periods for $\gamma = 0.2$, and after 60 periods for $\gamma = 0.5$. Withdrawing more than 1 million acre-feet per year (the steady state extraction level) becomes economically not viable. The extractions for no subsidy decline over time at a lower rate than the other two subsidy levels for 60 periods, and then exceed these levels for the remaining periods, although the total extractions (over 200 years) with no subsidy are lower (323 million acre-feet) compared to extractions levels with subsidy (342.9 million acre-feet for $\gamma = 0.2$ and 341.5 million acre-feet for $\gamma = 0.5$). The trend is monotonic; it outperforms the level with subsidy, reaching a steady state level of extraction after 200 periods at 1.2 million acre-feet.

Scrutiny of the water table depth, where the collapse of the aquifer is more evident, corroborates the aforementioned statements. The introduction of the subsidy results in the collapse of the aquifer, and the trend is smoother and more monotonic when there is no subsidy (i.e., $\gamma = 1$).

The comparison of the results of the decoupling and elimination policy interventions (Fig. 8) suggests the existence of a small difference in the number of units pumped in the first 150 periods under the decoupling policy compared with the number of units pumped under the elimination policy. This results in a difference in the water table depth, leaving the aquifer slightly deeper through the decoupling intervention.[1]

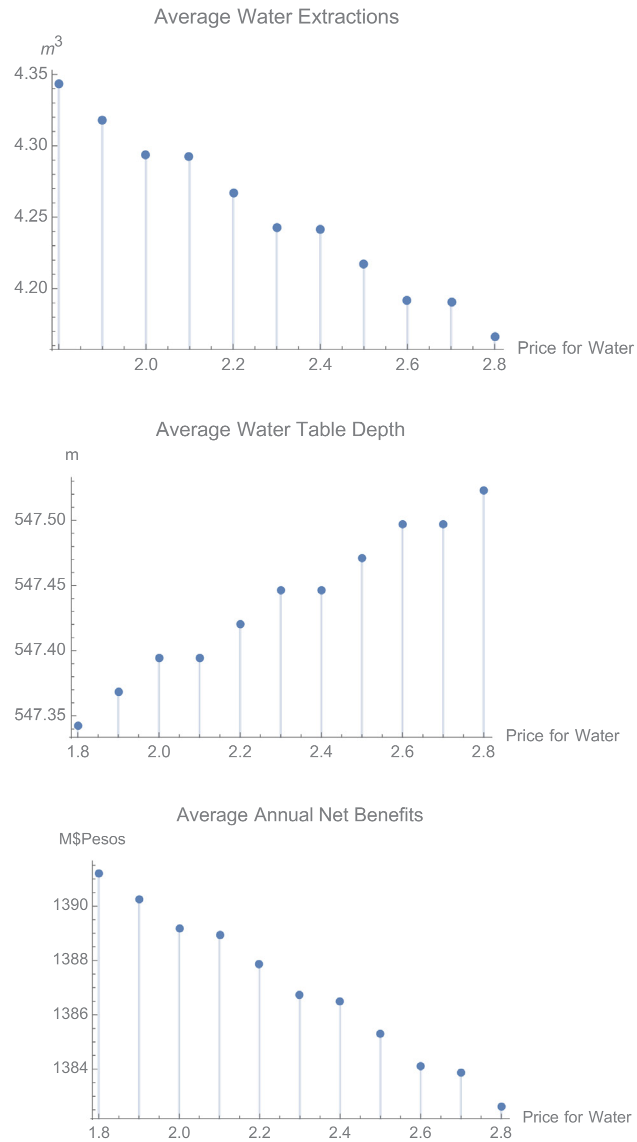

Fig. 6. Sensitivity analysis for water pumping cost.

4. Conclusions and policy implications

The present study focuses on an analysis of the effects of subsidy structures and policy modifications on sustainability of groundwater. The effects of different policy interventions are measured by introducing a subsidy for electricity in the cost function. The analysis results in several conclusions reported below on various institutional arrangements and policy interventions.

4.1. Common property vs. optimal behavior

The results across policy interventions for the common property behavior institution demonstrate that the possible collapse of the

[1] However, when compared with the water table depth, where $\gamma = 0.2$and $\gamma = 0.5$, the value is significantly less deep.

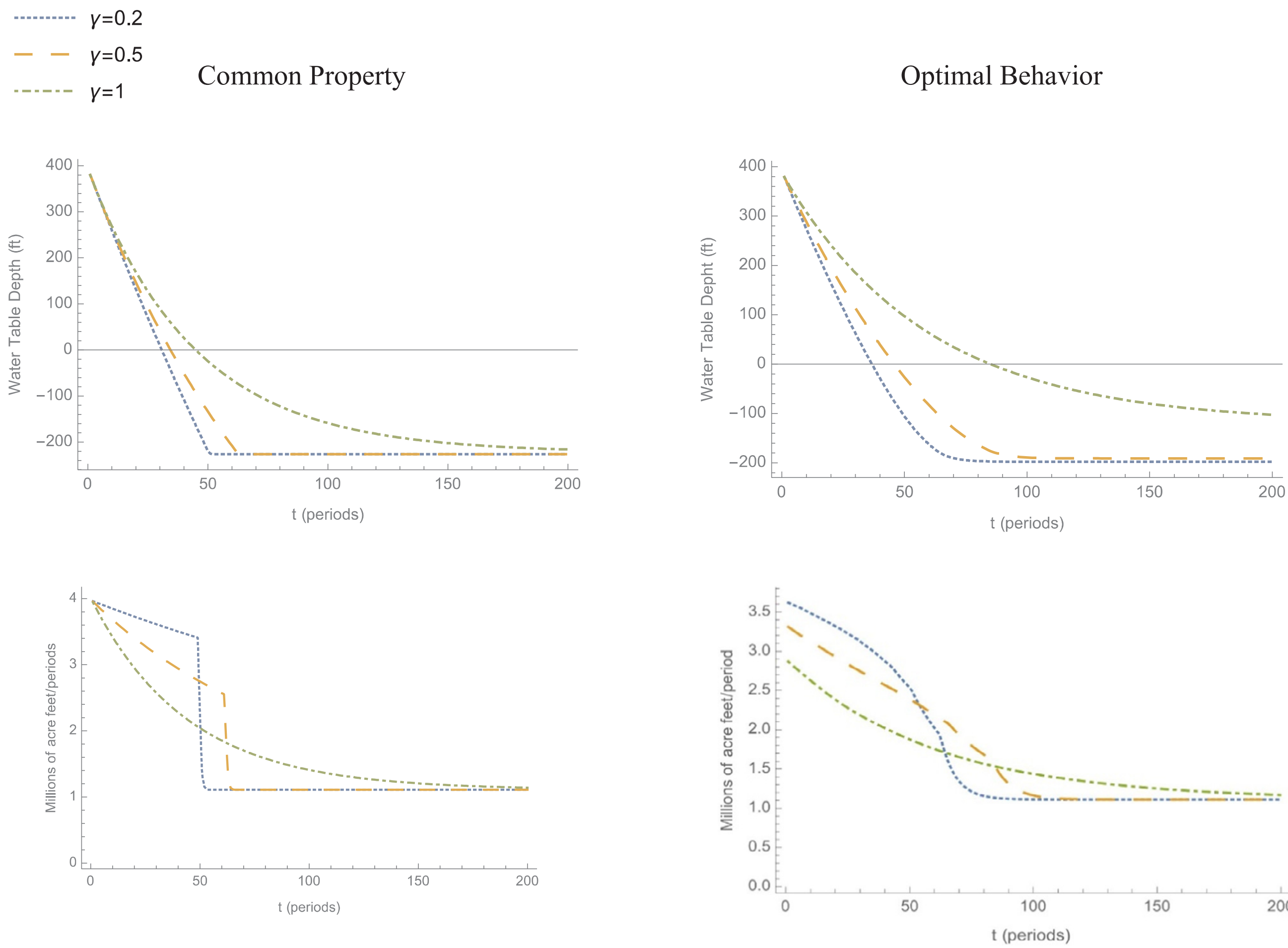

Fig. 7. Simulation analysis for Kern aquifer under common property and optimal behavior scenarios.

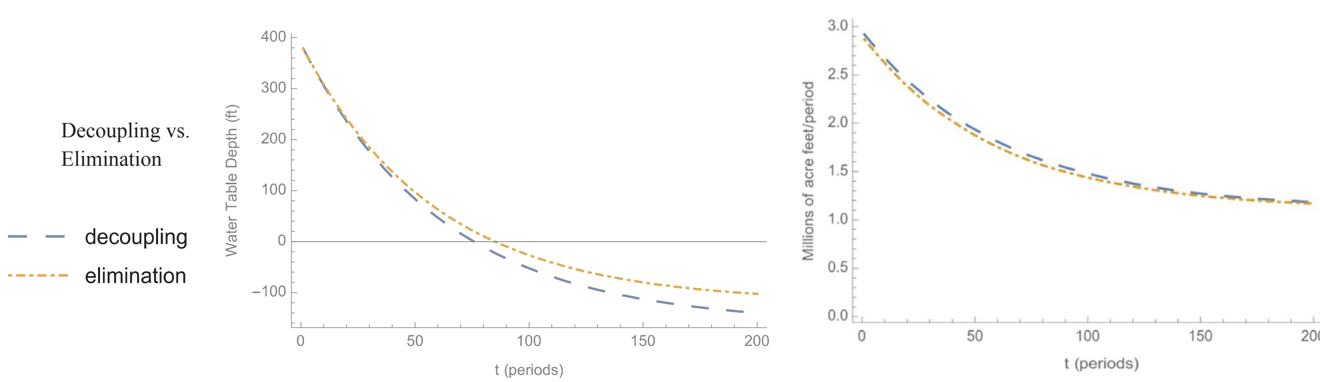

Fig. 8. Simulation analysis for Kern county aquifer: Decoupling and full elimination scenarios.

aquifer in the presence of the subsidy and the number of periods before the aquifer becomes economically not viable depend on the level of the subsidy, γ. The exception is the subsidy elimination policy where, even when the aquifer does not collapse under common property, higher level values of the water table depth are evident. The elimination and decoupling policies sustain the aquifer in a similar way because the common property behavior under the decoupling policy is the same as under the elimination case; the optimization problem takes into account only the benefit function and the cost function. The definition of common property solutions, identified by Feinerman and Knapp (1983), applies to users who behave myopically, considering only the marginal extraction costs and marginal benefit for the current period, and ignoring the costs imposed on others and themselves from future pumping, cash transfers that are not tied to the cost, and present benefit structures.

4.2. Policy modifications

Our analysis includes several policy interventions. We simulated subsidy levels by systematically changing the γ-values ($\gamma = [0.2, 0.5, 1.0]$). We also simulated the decoupling of the subsidy from the electricity price by providing a cash transfer equivalent to the annual average cost of extraction. The behavior of the users in our model changed systematically in response to these policy interventions.

In the case of Kern County we observed that introducing subsidy for electricity (i.e., $\gamma = [0.2, 0.5]$) leads to the collapse of the aquifer in fewer than 100 periods. However, eliminating the subsidy ($\gamma = 1.0$) caused the aquifer to reach a steady state that was shallower compared to the case that included a subsidy.

When introducing the decoupling policy, we observed that the results are close to those of the subsidy elimination policy, although the total present value of net benefits is slightly higher with decoupling. This result is consistent across different values of i, implying that the length of the lag used for calculating the decoupling factor has only a marginal impact on the long-term results. We do not consider in our paper the political economy associated with the selection of i.

The application to Kern county aquifer resulted in a similar behavior of the aquifer users' response to policy intervention as in Leon (although with some convexity differences), despite the differences in geological, economic, and legal-institutional characteristics. This gives rise to the hypothesis that the policy intervention results are robust and may be extended to other aquifers.

4.3. Sensitivity analysis

We have analyzed the model's sensitivity to variations in the electricity price. As expected, the model displays trends typical to a normal good, with a downward sloping annual net benefit when ξ increases, and a downward sloping water extraction with an increase in ξ. This finding is consistent with the behavior of the water table depth, where we observe that the aquifer becomes shallower as electricity prices decrease.

4.4. Policy implications

The econometric analysis performed by Muñoz et al. (2006) suggests that a 100% increase in the price of electricity leads to a decrease of 16% in the amount of water pumped from the aquifers. Our analysis suggests that the same percentage increase in electricity price leads to a reduction of 9% in the amount of water extracted from the aquifer. These results, along with the analytical results, suggest that changes in the subsidy lead to a reduction in the aquifer water pumped by farmers. The 16% and 9% values are considered to be inelastic and may not satisfy expectations of reduction in extraction. Additional policies may be needed, such as programs that allow farmers to adopt more efficient irrigation technologies and management practices. Having alternative option for responses, farmers may reduce their extraction even more and remain profitable.

Given the political power and strong lobby of farming organizations, it is politically not feasible to simply eliminate the subsidy. Therefore, we propose a different policy alternative for addressing this problem with a possibly lower social/political cost. Moreover, as discussed earlier, changes in the institutional arrangements are costly (both politically and economically), slow to implement, and in many cases irreversible. Our simulation results give rise to the hypothesis that decoupling is a feasible policy modification for achieving the stabilization of the over-drafted aquifer. Decoupling would have similar effects as would drastically reducing or eliminating the subsidy without the political burden associated with the latter policies. Whereas these results are based on computer modeling and computer simulations, the hypotheses drawn from them may be tested experimentally to validate the conclusions drawn from the theoretical results and generate superior policy recommendations.

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Appendix

Table A1
Parameter values used in simulations for Leon, Guanajuato, Mexico.

Parameter	Value	Units
ξ	2.722	Thousands of pesos/1 million m^3/m
$\bar{X}$	550	meters
α	0.95238095	–
g	490.39	pesos/m^3
k	85.81	pesos/m^3
β_{dp}	0.2	–
β_{sw}	0.3	–
q_{sw}	1.43	millions m^3
A	7.07	million m^3
γ	[0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]	–
S	0.13	–
R	1.56	millions m^3/year
Max depth	−126	meters

Source: CONAGUA (Comisión Nacional del Agua), 2010) and Muñoz et al., 2006.

Table A2
Parameter values used in simulations for Kern County, California.

Parameter	Value	Units
ξ	0.13	USD/acre-feet/foot
$\bar{X}$	385	Feet
α	0.95238095	–
g	146.9	USD/acre-feet
k	27.66	USD/acre-feet^2
β_{dp}	0.2	–
β_{sw}	0.3	–
q_{sw}	1.9	Millions acre-feet
A	1.29	Million acres
γ	[0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]	–
S	0.13	–
R	0.052	Millions acre-feet/year
Max depth	−233	Feet

Source: Feinerman and Knapp (1983).

References

Asad, M., Dinar, A., 2006. The role of water policy in Mexico: Sustainability, equity, and economic growth considerations (Working Paper No. 27). In: Latin America and Caribbean Region Sustainable Development. World Bank, Washington, DC, pp. 22.

Brozovic, N., Sunding, D. L., Zilberman, D., 2006. On the spatial nature of the groundwater pumping externality. In: Paper presented at the annual meeting of the American Agricultural Economics Association (New Name 2008: Agricultural and Applied Economics Association), Long Beach, California.

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

CONAGUA, (2009–2011). Estadísticas del agua. Comisión Nacional del Agua. Mexico.

Dinar, A. (Ed.), 2000. The Political Economy of Water Pricing Reforms. Oxford University Press, Oxford.

Dinar, A., Guerrero Garcia Rojas, H.R., Yunez-Naude, A., Medellin-Azuara, J., 2008. Politicas en el sector agua, instrumnmentos para la evaluacion de dus consecuencias economicas y ambientales. *Lecturas* 100, 11–29.

Dubash, N.K., 2007. The electricity-groundwater conundrum: case for a political solution to a political problem. Econ. Political Weekly 42, 45–55.

Esteban, E., Albiac, J., 2011. Groundwater and ecosystems damages: questioning the Gisser-Sánchez effect. Ecol. Econ. 70, 2062–2069.

Esteban, E., Albiac, J., 2012. The problem of sustainable groundwater management: the case of La Mancha aquifers. Hydrogeol. J. 20, 851–863.

Esteban, E., Dinar, A., 2016. The Role of Groundwater-dependent Ecosystems in Groundwater Management. Nat. Resour. Model. 29 (1), 98–129.

Feinerman, E., Knapp, K., 1983. Benefits from groundwater management: magnitude, sensitivity, and distribution. Am. J. Agric. Econ. 65, 703–710.

Gisser, M., Sanchez, D., 1980. Competition versus optimal control in groundwater pumping. Water Resour. Res. 31, 638–642.

Jain, V., 2006. Political economy of electricity subsidy: evidence from Punjab. Econ. Political Weekly 41 (38), 4072–4080.

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

Koundouri, P., 2004. Current issues in the economics of groundwater resource management. J. Econ. Surv. 18, 703–740.

Mukherji, A., Shah, T., 2005. Groundwater socio-ecology and governance: a review of institutions and policies in selected countries. Hydrogeol. J. 13, 328–345.

Muñoz, C., Avila, S., Jaramillo, L.A., Martinez, A., 2006. Agriculture Demand For Groundwater in Mexico: Impact of Water Enforcement and Electricity User-Fee On Groundwater Level and Quality. Instituto Nacional de Ecología Working Paper INE-DGIPEA/0306.

Myers, N., 1999. Perverse subsidies. R. Soc. Encouragement Arts RSA J. 147, 84–91.

Nasim, S., Helfand, S., 2015. Optimal groundwater management in Pakistan's Indus Water Basin. IFPRI Working Paper 34, http://www.ifpri.org/publication/optimal-groundwater-management-pakistans-indus-water-basin.

Parker, J.A., 2008. Euler equations. The new Palgrave dictionary of economics. In: Durlauf, S.N., Blume, L.E. (Eds.), The New Palgrave Dictionary of Economics. Palgrave Macmillan.

Pearce, D., 2003. Environmentally harmful subsidies: Barriers to sustainable development. Environmentally harmful Subsidies: Policy issues and challenges. OECD, Paris, pp. 9–32.

Shah, T., Singh, O., Mukherji, A., 2006. Some aspects of South Asia's groundwater irrigation economy: analyses from a survey in India, Pakistan, Nepal Terai and Bangladesh. Hydrogeol. J. 14, 286–309.

Shah, T., Sonal, B., Shah, R.K., Talati, J., 2008. Groundwater governance through electricity supply management: assessing an innovative intervention in Gujarat, western India. Agric. Water Manage. 9 (5), 1233–1242.

Suter, J.F., Duke, J.M., Messer, K.D., Michael, H.A., 2012. Behavior in a spatially explicit groundwater resource: evidence from the lab. Am. J. Agric. Econ. 94, 1094–1112.