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TABLE OF CONTENTS

Comparing Alternative Modifications of Energy Subsidies: The Case of Groundwater Extraction

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Summary:

This paper analyzes the responses of profit maximizing groundwater users to modifications (elimination, reduction, decoupling) of the subsidy to electricity frequently used for water pumping. It proposes a theoretical model, and numerically derives general results for a simplified case with homogeneous users. The model is applied to aquifers in Leon, Guanajuato, Mexico and in Kern County, California. We propose a method to compare the performance of a new, innovative policy intervention—decoupling the subsidy from the electricity bill—with two traditional policy interventions, elimination and reduction of the subsidy. The results suggest that the rate of water extraction of and the level of water in the aquifer, which are undesirable under the existing electricity subsidy, can be improved by changing the subsidy structure. Furthermore, decoupling represents a politically feasible alternative to solving the overexploitation of groundwater due to electricity subsidies.

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1 Introduction

Scarce natural resources are regulated in many countries by subsidies. In many, though not all, cases subsidies have perverse effects on the economy and the environment. Perverse subsidies were estimated at one point to reach $1,450 billion dollars per year, and are held accountable for $30 trillion distortion damages (Myers, 1999). In the developing world, subsidies to groundwater (GW) pumping account for at least $45 billion dollars annually; meanwhile agricultural subsidies (including irrigation subsidies) reach $65 billion dollars in developing countries and up to $335 billion dollars in developed countries (Pearce, 2003).

Electricity subsidies for pumping GW present a major challenge for regulators around the world. For example, Mexico, India, and Pakistan have implemented subsidies for electricity used to pump GW in an effort to render the agricultural sector more competitive. This issue becomes socially crucial because the number of people depending on GW is significant. For example, 55-60 percent of the population in India relies on GW, which is mainly used for agricultural production (Mukherji & Shah, 2005). It is perhaps not surprising that in some regions of India the electricity subsidy is used as a political tool, where some regions take an extreme approach of no charge for electricity at all as is the case in Punjab (Shah et al., 2006; Jain, 2006).

Shifting the focus to Mexico, a total volume of 29.5 km^3 is extracted annually from GW sources. Of this amount, 70 percent is used in irrigated agriculture. The Mexican government decided in the early 1990s to provide a subsidy to electricity used in pumping water for irrigation. The subsidy—"Tarifa 09"—is volumetric; it is provided to farmers based on the electricity level they consume for pumping GW. As a result of the subsidized pumping cost and other policies, out of the 188 major aquifers in Mexico, 101 have been over-drafted due to mismanagement practices and lack of incentives to use appropriate irrigation technologies (Muñoz et al., 2006). These bad practices are blamed mainly on the perverse water and electricity subsidies (Asad & Dinar, 2006; Dinar et al., 2008).

According to the Mexican National Water Law, water used for irrigation is not priced. Rather, farmers have to pay only for the costs of extracting water (either from surface or GW sources). It is evident that the set of incentives to the farmers hides the real costs of pumping not only because the cost of pumping is subsidized but also because there does not exist a price that reflects scarcity and negative externalities; therefore, the current institutional framework leads to inefficient exploitation of groundwater resources.

1.1 Previous work

There is a vast body of literature concerning GW extraction and electricity use, which points to the intrinsic relationship between these two economic goods. Most of the literature focuses on the inefficiencies of water allocation due to incorrect price signaling of electricity to farmers. Shah et al. (2005) have analyzed the GW irrigation economy in South Asia, using results of a survey among GW users in India, Pakistan, Nepal, and Bangladesh. Some of their main conclusions are that GW resources are over-extracted, and that energy pricing has undoubtedly shaped South Asia's GW economy. They also report that the subsidy is regressive because mostly rich landowners have access to electric pumps, whereas poor farmers choose diesel pumps, or buy water from their rich neighbors. Dubash (2007) analyzes the inherent relationship between electricity and GW by assessing the effect of subsidies on GW consumption using the Indian case as example. His findings coincide with those of Shah et al. (2005) regarding the regressive nature of the subsidies for electricity. Dubash (2007) also assesses the impact of this subsidy on the quality of the electricity service provided by the State Electricity Board of India. He finds that farmers prefer receiving a poor quality service as long as they continue receiving the subsidy. In another study, Mukherji and Shah (2005) discuss the institutional arrangements and policies related to GW in India, Pakistan, Bangladesh, China, Mexico, and Spain. On the basis of a set of six country cases, they conclude that even though there exists a wide range of situations across these cases regarding the institutional arrangement, the understanding of the social and economic impact of GW is still poor, and the scientific knowledge in the field of GW is biased towards the resource and its development rather than the externalities created by its use.

The GW literature focuses also on the implications of control policies. Gisser and Sanchez (1980) analyze the benefits of command and control versus market allocation of GW. They present a dynamic model that maximizes present value of net benefit in a case of a very large aquifer, and then conclude that the changes in welfare associated with central regulation (pricing, quotas) of GW are negligible. Feinerman and Knapp (1983) support this conclusion; they analyze the problem of GW allocation using a dynamic model similar to the one used by Gisser and Sanchez (1980) and apply it to the Kern County aquifer in California. Their results suggest that the social benefits of implementing command and control mechanisms (i.e., pumping quotas) are quite small compared to the status quo (Feinerman and Knapp, 1983:709).

On the other hand, applying their analysis to the Eastern and Western La Mancha aquifers in Spain, Esteban and Albiac (2011, 2012) conclude that when taking into account the environmental damage caused by over-drafting GW resources, the benefits of implementing command and control policy are important because of the public nature of the environmental amenities of GW. The authors reported evidence that supports their analytical conclusions.

Other studies such as Burness and Brill (2001) discuss the role of policy in the case where farmers can switch technologies; the authors find that regulation can cause switches to more efficient technology because the future costs of pumping become more explicit. Kim et al. (1989) discuss adaptation of the farmers' behavior, particularly via crop choices, when the price of extracting groundwater water increases. Their findings suggest that under social optimal behavior, farmers switch away from water intensive crops (sorghum) twice as fast as in the common property behavior, thereby increasing the benefits from groundwater use.

So far we have presented results of analyses of energy cost impacts reported in the literature on GW management. While the results are broad and rich, shedding light on the complex conundrum of GW, energy, and other inputs, more research is needed in order to analyze alternative policy options for dealing with energy subsidy, which could help solving the GW overexploitation problem. Muñoz et al. (2006) propose different ways to modify the electricity subsidy and reduce extractions to a level that could help stabilize the over-drafted aquifers. These measures include the two traditional policy interventions—elimination and reduction of the subsidy, and also the option of decoupling the subsidy from the electricity price and giving farmers a cash transfer in the amount of the subsidy. Decoupling can be introduced in several ways 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.

These alternative mechanisms (reforms) help solving some problems but creating others. Thus, grandfathering is close to status quo; it might create an incentive to draw more water than prior to the reform in order to get a better financial transfer after the reform. The surface-based decoupling system might promote an increase in the irrigated surface. And the egalitarian choice might help solving the concentration of the subsidy; however, it may negatively affect the big producers.

Our study develops and applies a model that focuses on the potential changes in behavior due to a change in the subsidy mechanism (e.g., complete elimination, decoupling, and reduction cases are considered). We use a dynamic optimization model described in Section 3 to analyze the changes in GW extraction under these different mechanisms. The model is applied to data from León, Mexico and Kern County, California (in a robustness check at the end of the paper) in order to evaluate the effectiveness of the three policy interventions described above under optimal extraction behavior and common property behavior of the users.

2 A dynamic model of demand for groundwater with subsidy for electricity

In this section, we propose a dynamic model based on previous work by Gisser and Sánchez (1980), Feinerman and Knapp (1983), Esteban and Albiac (2011), and Brozovic et al. (2006). The model introduces subsidy as part of the cost function, which has not been done in previous work, and then implements various subsidy modification policies to simulate the alternative subsidy treatments under consideration. The model uses the simplifying assumption that all GW users are homogenous, and that each has a single technology for extracting water (electric pumps).

2.1 Water demand

The water demand function is represented by

$$W_t = g + kP,$$

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

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

where we define

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

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, β_{sw} is the amount of surface water that goes back into the aquifer, and our control variable is the amount of groundwater consumed, which is denoted by w.

2.2 Extraction costs

Extraction costs are represented by

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

where

$$C_1(\gamma, x_t, \xi, w_t) = \gamma\xi(X - x_t)w_t.$$

The term C_t in equation (2) is the total cost to pump w units of groundwater at time t, C_0 is the fixed cost, C_1 is variable cost, which is a function of the water table (x_t), and the cost of the total electricity required to lift one million m^3 of water (ξ). X is the distance of the land surface from the bottom of the aquifer.

The constrained maximization problem for the entire aquifer (where all farmers are assumed to be homogenous) looks as follows:

$$\max_{w_t} \sum_{t=1}^{\infty} \alpha^t \{gq_t - \tfrac{1}{2}kq_t^2 - C_0 - [\gamma\xi(X - x_t)w_t]\} \qquad (3)$$

$s.t.$

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

The term R in equation (3) is the recharge, 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 of the aquifer, and α^t is the discount factor, where $\alpha = \frac{1}{1+r}$, r is the discount rate, and x is the pumping lift. All lifts and pumping distances are measured with respect to the mean sea level as done by Feinerman and Knapp (1983).

Within this model, we may vary the level of subsidy by changing the values of γ to simulate the different treatments or levels of subsidies. Both common property and optimal behavior scenarios are investigated using computer simulations for 200 periods and parameters from the aquifers in Leon, Guanajuato, Mexico. Lastly, decoupling of the subsidy is tested by charging the users the full price of electricity and then having them receive a money transfer equivalent to their average subsidy relative to their electricity consumption in the previous i periods.

2.3 Results for common property extraction behavior

Under the common property extraction behavior, (myopic) users are assumed to have little or no incentives to take into consideration the future costs of pumping. Consequently, users are expected to 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:

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

It is obvious that a lower marginal extraction cost (effect of the subsidy level γ) will induce a larger quantity of water extraction at time *t*, ignoring any future cost.

With equation (4), we can derive our groundwater demand under the common property condition:

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

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 ($\gamma = 1$).

Below we present simulation results of the common property extraction behavior for the level of extraction (Figure 1) and for the water level in the aquifer (Figure 2) using parameters for the aquifer of Leon, Guanajuato, Mexico.

Figure 1. Groundwater Extractions under Common Property Behavior

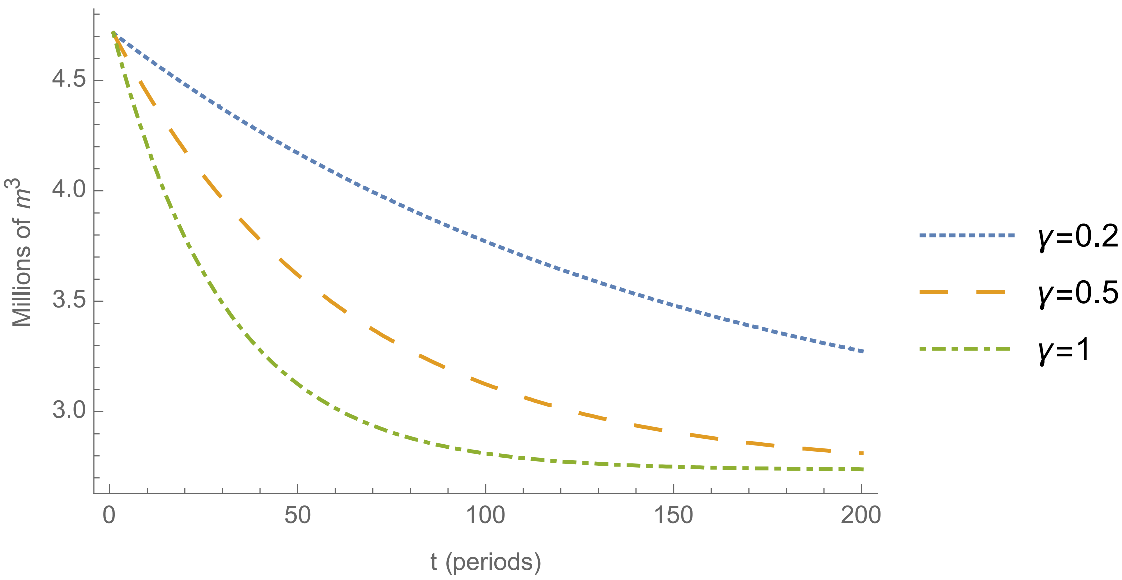
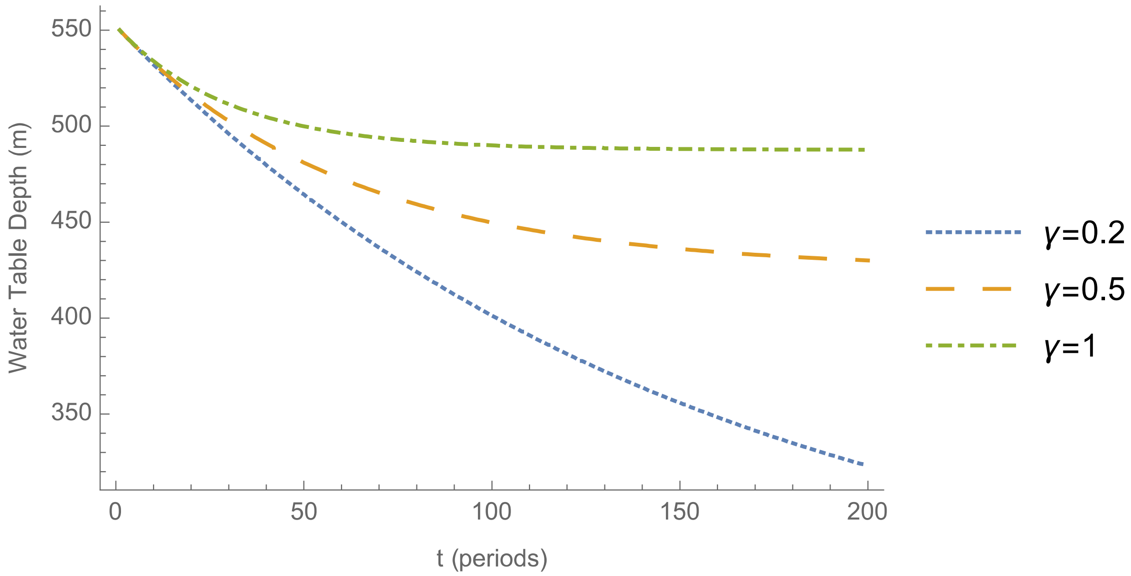


Figure 1 exhibits the extraction per period for the common property extraction behavior under three different policy scenarios. It shows clearly that once the subsidy is introduced the distortion effect leads to a greater rate of extraction from the aquifer. A lower steady state level was reached after 90 and 130 periods respectively, for $\gamma = 1$ and 0.5. No steady state was reached for $\gamma = 0.2$ within the 200 period horizon.

The aforementioned statements become clearer following scrutiny of Figure 2, where the collapse of the aquifer is more evident. One may clearly observe how the introduction of the subsidy results in the collapse of the aquifer, and that the trend of water depth is smaller and kept at a higher level where there is no subsidy ($\gamma = 1$).

Figure 2. Water Table Depth under Common Property Extraction Behavior



2.4 Results for optimal extraction behavior

Under optimal extraction behavior, the users optimize their water extraction not only according to their marginal extraction cost but also according to the marginal user cost (the reduction in the discounted future net benefits from a withdrawal of one additional unit in the current period (Feinermann and Knapp, 1983)). Therefore, the optimal extraction cost follows an optimal path that takes into account the present and future consequences of the extraction decision.

Recalling our optimization problem stated in equation (3), we derive the Bellman equation:

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

The Bellman equation simplifies our infinite horizon problem into a two-stage discounted function that we may use to compute the optimal path of extraction.

From the Bellman Equation we can derive the first order conditions that yield the following Euler Equation:

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

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

The Euler Equation is used to derive the optimal path of GW extraction. It represents the marginal change of behavior by having the marginal net benefits equal the marginal costs in the present and in the (discounted) future (Parker, 2008). It is clear that raising the value of γ from 0.2 to 1 increases the present cost (right hand side of the equation); however, it also increases the marginal (discounted) benefit in the future (left hand side of the equation. Therefore, we may anticipate that modifications of the subsidy will lead to a deviation from the extraction path with subsidy, which will lead to a shallower steady state of the water table.

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

$$w_t = \alpha \frac{AS(\gamma\xi(x_t - \bar{X}) + kq_{sw}(\beta_{sw} - 1) + 1)}{ASk}$$

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

We have simulated the model for 200 periods using three different policy scenarios for subsidy reduction and elimination ($\gamma = 0.2,\ \gamma = 0.5, and\ \gamma = 1$), with parameters from Leon, Guanajuato as presented in Annex Table 1A we obtain the following results that are presented in Figures 3 and 4.

Figure 3. Groundwater Extraction under Optimal Behavior

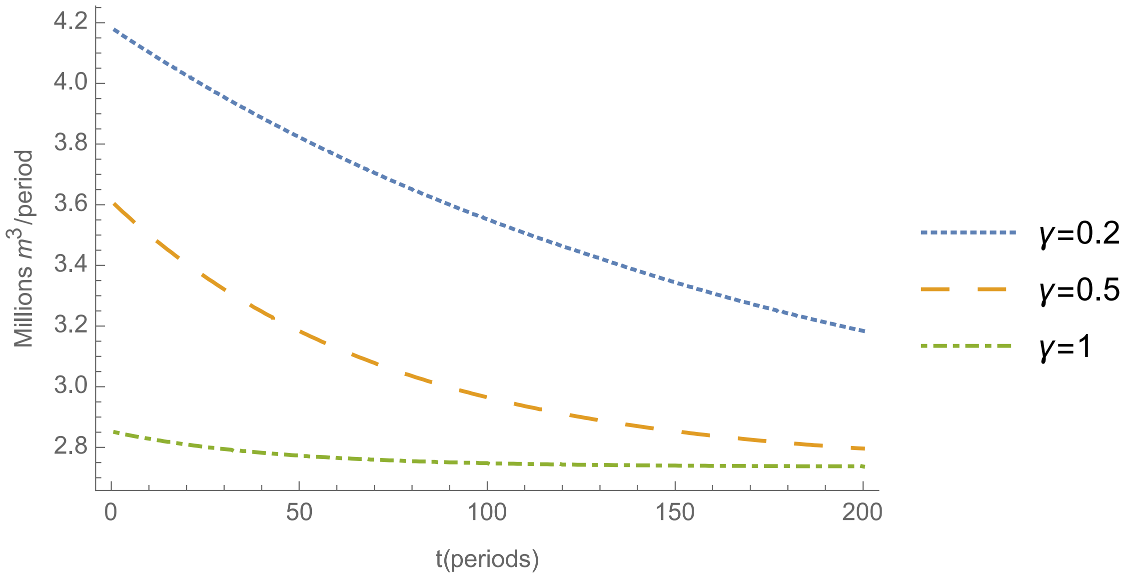


Figure 3 suggests that in the presence of subsidy the amount of water pumped is highest, and no steady state is reached for the case of $\gamma = 0.2$, which is consistent with the common property case. However, the figure shows that eliminating the subsidy induces a steady state at earlier periods (after 50 years in the case of $\gamma = 1$, and after 150 years in the case of $\gamma = 0.5$.

Figure 4. Water Table Depth under Optimal Extraction Behavior

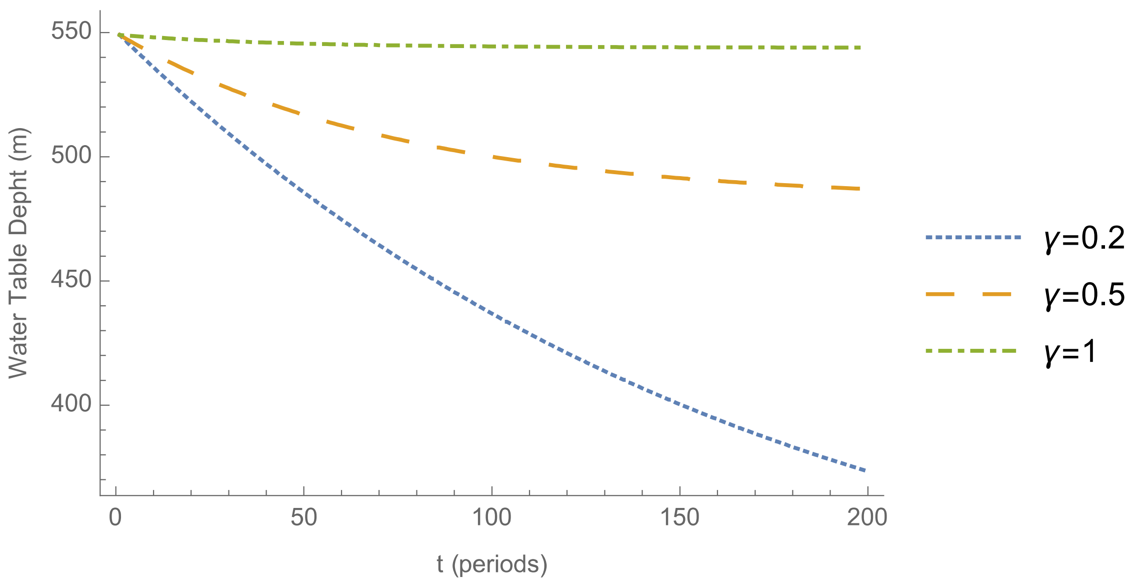


Figure 4 confirms the aforementioned statement by exhibiting that the water table depth converges almost immediately to a steady state when the subsidy is eliminated, reaching a steady state after 70 years with $\gamma = 0.5$, and keeps a downward sloping trend when $\gamma = 0.2$. Depth of water table is also the lowest when the subsidy is eliminated.

2.5 Decoupling the electricity subsidy

The analysis presented above includes two obvious policy modifications aimed to fix or attenuate the distortions caused by the subsidy for electricity, namely, reducing and eliminating the subsidy, represented, respectively, by the values $\gamma = 0.5$ *and* $\gamma = 1$. However, these two policies do not take into account the political economy of the subsidy modification. Frequently, irrigation districts and farm unions comprise a very powerful and influential political power with a strong lobby within the local and national governments of the countries that subsidies energy for irrigation. Therefore, political influence of agricultural lobbies destructs in many cases the subsidy reduction policy. Decoupling of the subsidy from the electricity rate and returning the equivalent sums back to the users may act as subsidy elimination but without the political cost associated with subsidy elimination. This assertion is supported by research conducted by Muñoz et al (2006), as was discussed in section 2.

To analyze the impact of decoupling the electricity subsidy, we need to modify our optimization problem to include the average cost of electricity paid in the previous i periods. The optimization problem with decoupling will now be:

$$\max_{w_t} \sum_{t=1}^{\infty} \alpha^t \{ g q_t - \frac{1}{2} k q_t^2 - C_0 - [\gamma \xi (X - x_t) w_t + \phi] \} \qquad (9)$$

$s.t.$

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

where

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

The term ϕ in equation (9) is the decoupling factor that ranges from $(\tau - i)$ to τ, with $\tau < \infty$ being a predetermined number of periods and i being the number of periods that will be used to calculate the average electricity cost of pumping. 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:

(10)

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

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

$$w_t = \alpha \frac{AS\gamma\xi\bar{X}(1-i) + (\beta_{dp}-1)\left(\frac{\gamma(i-1)\xi(AS(\bar{X}-x_{t+1}) + (\beta_{dp}-1)w_{t+1})}{(\beta_{dp}-1)i}\right)}{ASki}$$

$$+ \frac{AS(gi+\beta_{sw}ikq_{sw} - ikq_{sw} + \gamma\xi(ix_t - x_t)}{ASki} . \qquad (11)$$

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

$$w_t = \alpha \frac{AS(\gamma\xi(x_t-\bar{X}) + kq_{sw}(\beta_{sw}-1)+1)}{ASk} \qquad (12)$$

$$+ \frac{(\beta_{dp}-1)\left(w_{t+1}\gamma\xi - \frac{AS(g+\gamma\xi(x_{t+1}-\bar{X}) - k(-\beta_{sw}q_{sw} + q_{sw} + w_{t+1))}}{\beta_{dp}^{-1}}\right)}{ASk}$$

The model was simulated for 200 periods with $i = [3, 5, 10, 15]$. This means that the decoupling factor was calculated separately for the preceding 3, 5, 10 and 15 periods. The choice of the value of i is not arbitrary; the literature suggests using 3-period lag (Muñoz et al, 2006). For our simulations, we decided to study the effects of four different values of i because land use and the subsequent water use can drastically be affected by short-term shocks (economic and environmental). Moreover, in semi arid climates, like in the State of Guanajuato, these shocks may result in an important variability in short-term land use. Therefore, there is an advantage in using longer lags when calculating the decoupling factor.

The results of the simulations for subsidy elimination and for subsidy decoupling for $i = 15$ are presented in Figure 5 for extraction level, water table level, and annual net benefits.

Figure 5. Groundwater Extractions and Water Table Depth under Decoupling and Elimination of Subsidy

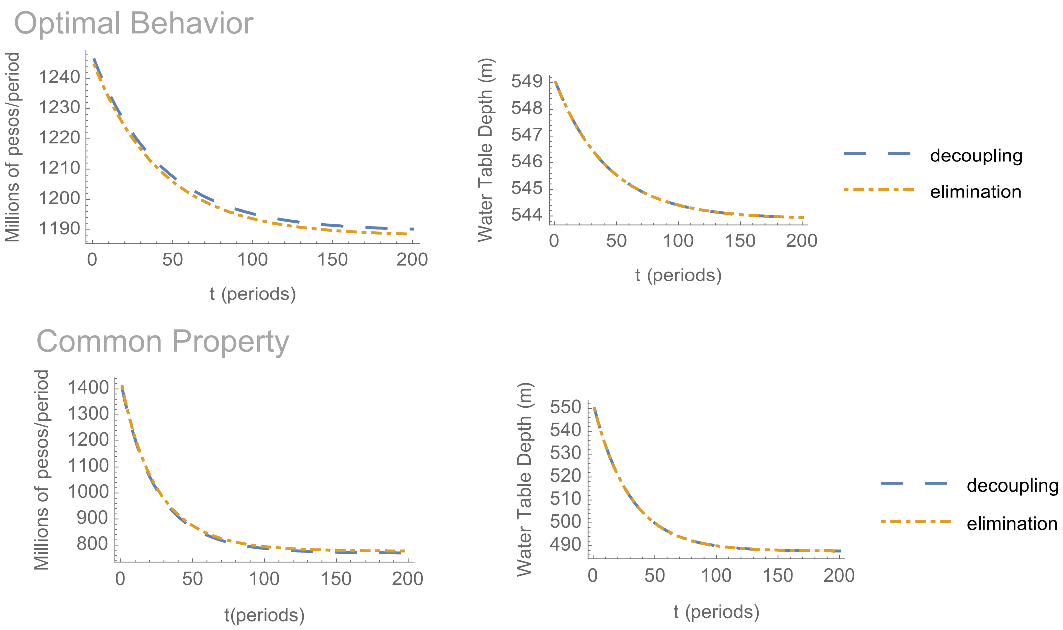


Figure 5 suggests that under decoupling we achieve the same results as when the subsidy is eliminated. However, when comparing the annual net benefits under decoupling and elimination of the subsidy, we observe that the total net present value of benefits under decoupling (for *i*=15 years) is 241,488 million Pesos for the 200 periods compared with 240,024 million Pesos for the case of elimination. The difference (0.6%) is due to the fact that the cash transfer under decoupling enters as part of the benefit function as a constant lump sum and it fades away when we take the first order conditions.

We have checked the difference in net present value of benefits for the various values of *i* (Table 1) for *i=3, 5, 10, 15*. Table 1 shows that the difference between the values is relatively small and declines as *i* decreases, so that we can conclude that in the long run the length of the decoupling factor has marginal impact on the user decisions. However, there is an advantage for using longer lags for calculating the decoupling factor. With longer periods of time the average pumping cost is less affected by exceptionally dry years, where the surface water supply could be affected, leading to higher water consumption that is not related to the subsidy.

Table 1. Total Net Present Value of Net Benefits over 200 Periods across Different Number of years

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]

[a]Note: In parentheses are the percentages values compared to i=15.

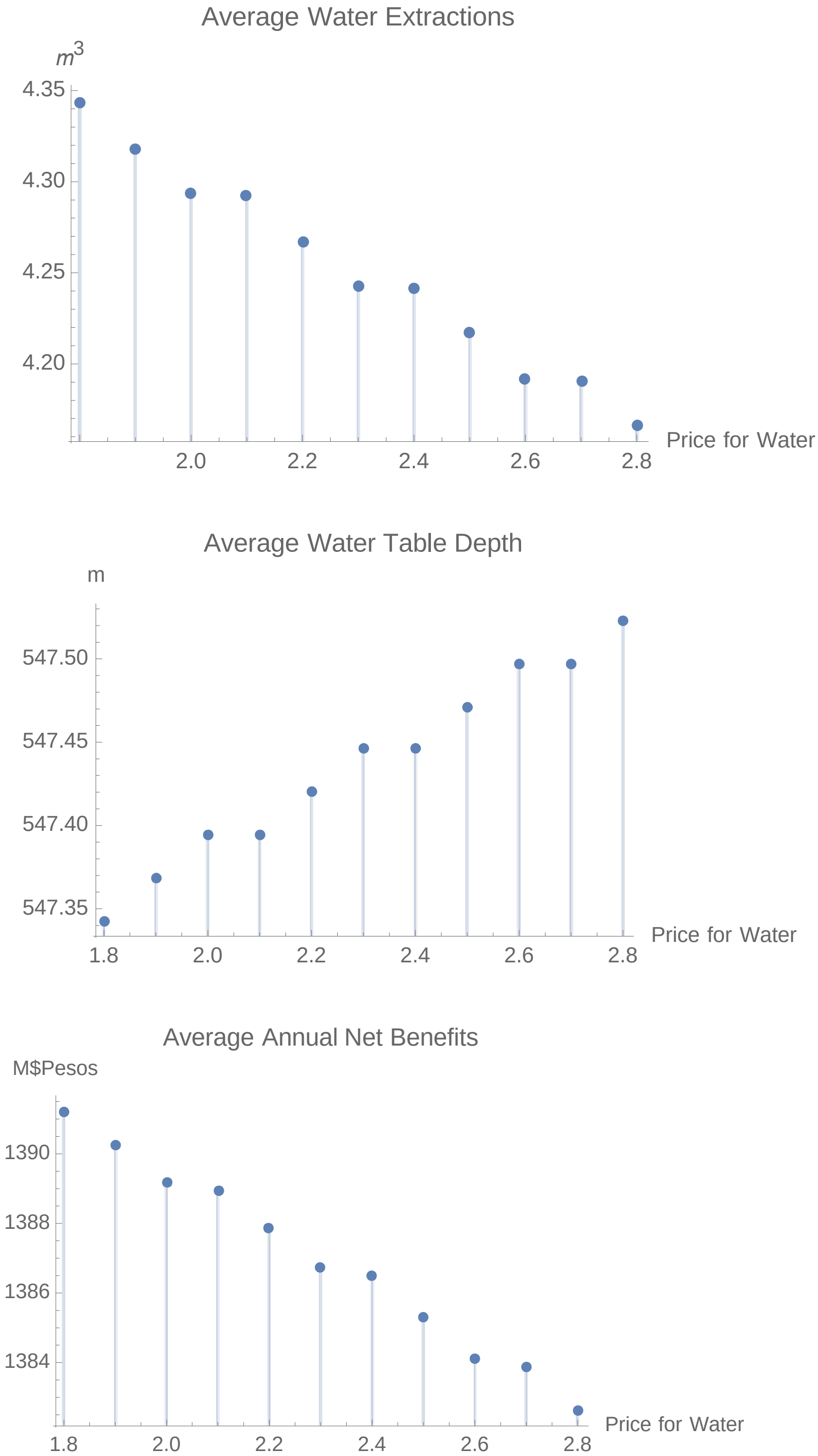
As stated by Dinar (2000), water-pricing reforms may spark both support and opposition by various affected groups, highlighting the importance of compensation mechanisms for ameliorating the losses of the affected groups. In our case, the decoupling transfer acts as a compensation mechanism that attenuates the political implications of the groundwater price reforms (in the form of changing the subsidy structure for electricity prices). This conclusion is supported by Muñoz et al (2006), who argue that the decoupling mechanism can raise the overall level of utility of farmers by giving them the option of allocating the subsidy money in any good way they get the most utility from, and not constraining it to electricity consumption.

Therefore, we may surmise that the decoupling policy intervention is viable, given the less controversial political economy implications of this policy intervention versus eliminating or reducing the subsidy. In addition, this policy modification provides additional positive environmental implications of preserving the aquifer that are not the subject of this research but that can be accounted as positive benefits.

3 Sensitivity Analysis

To test the behavior of the model when facing changes in the price for electricity, a sensitivity analysis was conducted by varying ξ from 1.8 to 2.8 thousand Pesos per 1 million m^3/m. The results (Figure 6) reveal that the model behaves as expected; we observe that the aquifer gets deeper when electricity prices decrease; we also observe that water extraction increases when electricity prices decrease and the annual net benefits decrease as ξ increases.

Figure 6. Sensitivity Analysis for Water Pumping Cost



4 Robustness

We conducted simulations for another aquifer to test for the robustness of the results. For this purpose, we used a set of parameters from Feinermann and Knapp (1983) shown in Annex Table 1B, for an aquifer in Kern County, California. Kern County has similar weather characteristics as the central region of Mexico, where the Leon aquifer is located. Both regions are semi arid and rely on groundwater supply for agriculture; however, some economic and geologic characteristics are different. Figure 7.1 exhibits the results for the Kern aquifer.

Figure 7.1. Sensitivity Analysis for Kern Aquifer under Common Property, Optimal Behavior Scenarios

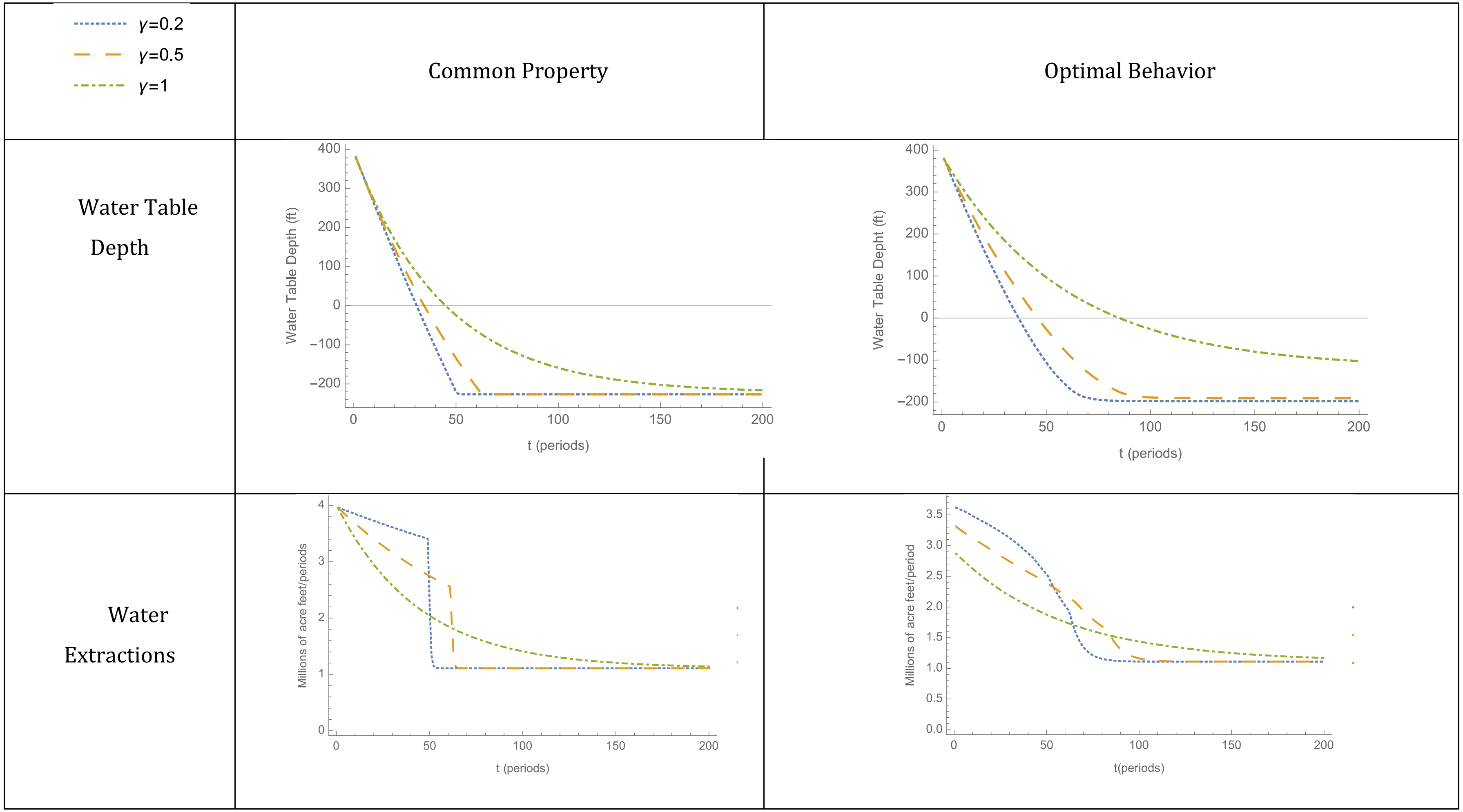
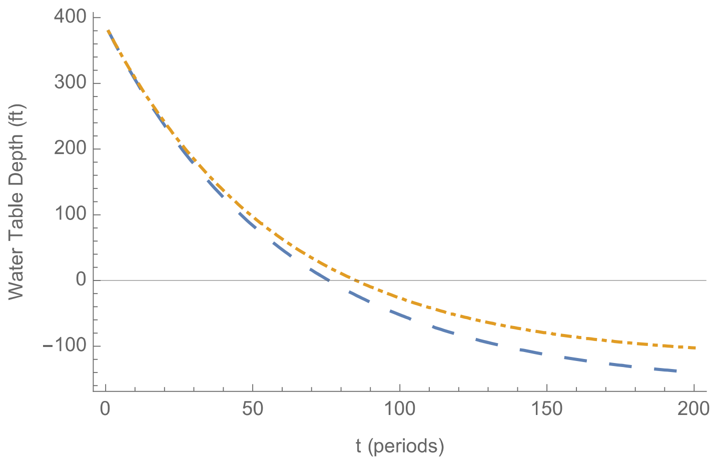


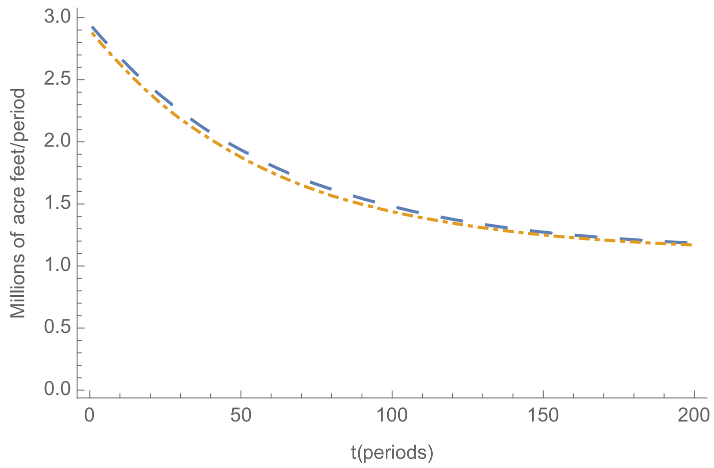
Figure 7.2. Sensitivity Analysis for Kern Aquifer: Decoupling, and Full Elimination Scenarios

Decoupling vs Elimination

decoupling

elimination





The results in the case of the common property extraction behavior, restricted to the level of extraction and for the water level in the aquifer that we have chosen, show that a lower, and higher steady state level was reached after 50 and 60 periods, for $\gamma = 0.2 \, and \, 0.5$, respectively, compared to a steady state, which has been reached after 200 periods for no subsidy ($\gamma = 1$).

It is clear that once the subsidy is introduced the distortion effect leads to the collapse of the aquifer (after 50 periods for $\gamma = 0.2$ and after 60 periods for $\gamma = 0.5$). This means that it becomes economically unviable to withdraw more than 1 million acre-feet a year (the steady state extraction level). We also observe that the extractions for the case of no subsidy are declining over time at a lower rate than the other two subsidy levels for 60 years, and exceeding it for the rest of the period, although the total extractions (over 200 years) with no subsidy are lower (323M acre-feet) compared with any subsidy level (342.9M acre-feet for $\gamma = 0.2$ and 341.5M acre-feet for $\gamma = 0.5$). The trend is monotonic and outperforms the case with subsidy, reaching a steady state level of extraction of 1.2 million acre-feet after 200 periods.

Inspection of the water table depth, where the collapse of the aquifer is more evident, corroborates the aforementioned statements. We can clearly observe how the introduction of the subsidy results in the collapse of the aquifer, and that the trend is smoother and monotonic where there is no subsidy (i.e. $\gamma = 1$).

The comparison of the results from decoupling to the elimination intervention (third row) suggests the existence of a slight deviation of 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 slight difference in the depth to water table, leaving the aquifer slightly deeper with the decoupling intervention[2].

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

5 Conclusions and policy implications

The present research focuses on the analysis of the effects of different subsidy structures and policy modifications on sustainability of GW, given the perverse incentives provided by electricity (or more generally, energy) subsidies for GW pumping in the farming sector. By embedding the subsidy in the cost function we were able to measure the effect of different policy interventions. Our analysis gives rise to several conclusions that are reported below with respect to various institutional arrangements and different policy interventions.

5.1 Common Property vs. Optimal Behavior

When analyzing the results across policy interventions for the common property behavior institution, we observe that the aquifer will collapse in the presence of the subsidy, and that the number of periods before the aquifer becomes economically unviable will depend on the rate of the subsidy, γ. The exception is for the subsidy elimination policy where, even when the aquifer does not collapse under common property, we can observe higher levels of the water table. We also observe that the elimination and decoupling policies are very similar in various measures of sustaining the aquifer. This is due to the fact that the common property behavior under the decoupling policy is exactly the same as under the elimination case because the optimization problem takes into account only the benefit function and the cost function. That is because the definition of common property solutions, such as the ones found in Feinerman and Knapp (1983), applies to myopic users who consider only the marginal extraction costs and marginal benefit for the current period and ignoring everything else (e.g., the cost imposed on others and themselves from future pumping, cash transfers that are not tight to the cost, or benefit structure at the present, etc.). In the next paragraph, we address the conclusions obtained from the various policy modifications under both institutions (common property and optimal use).

5.2 Different Policy Modifications

Our analysis includes different policy interventions, which are displayed in Annex Table 1A and 1B. We have simulated subsidy levels by systematically changing the value of $\gamma = [0.2, 0.5, 1.0]$. We also have simulated the decoupling of the subsidy from the electricity price and giving a cash transfer equivalent to an average cost of extraction. We could observe how the behavior of users in our model changed in response to these policy interventions.

With regards to the aquifer in Kern County, we observe that the introduction of electricity subsidy (i.e., $\gamma = [0.2,0.5]$) leads to the collapse of the aquifer in less then 100 periods. However, when eliminating the subsidy ($\gamma = 1.0$) the aquifer reaches a steady state of a water table level that is less deep compared with the case of a subsidy.

When introducing the decoupling policy intervention, we observe that the results follow very closely the subsidy elimination policy, although there is marginal difference in the total net present value of net benefits, which slightly higher for decoupling.

This result is consistent across different values of i, implying that the length of the lag used for calculating the decoupling factor has a marginal impact on the long-term results. However, we do not consider in our paper the political economy associated with the selection of i.

We observe the same behavior for Kern County parameters despite the difference in geological and economic characteristics. Therefore, we conclude that the policy intervention results are robust and may be extended to different aquifers.

5.3 Sensitivity Analysis

We have conducted tests to analyze the sensitivity of the model results to variations in the electricity price. As expected, the model displays trends typical to a normal good, with downward sloping annual net benefits when ξ increases, and downward sloping water extractions with increase in ξ. This is consistent with the behavior of the water table depth, where we observe that the aquifer gets deeper as electricity prices decrease.

5.4 Policy Implications

The econometric analysis performed by Muñoz et al (2006) suggests that a 100 percent increase in the price of electricity leads to a decrease of 16% in the amount of water pumped from the aquifers. These results, and the analytical results derived from the model in Section 3, lead us to expect a reduction in the water pumped by farmers from the aquifer with changes in the subsidy. The importance of this finding is that, given the political power that the farmer organizations bear and the strong lobby they mobilize, it is politically infeasible to simply eliminate the electricity subsidy. Therefore, we propose a different policy alternative to address this problem with 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. In addition, decoupling would have similar effects as drastically reducing or eliminating the subsidy without the political burden that the latter policies implicate. While these results are based solely on computer modeling and simulations, the hypotheses drawn from such results may be tested experimentally in order to strengthen the conclusions drawn from the theoretical results and generate better policy recommendations.

Annex

Table 1A: Parameters used in simulations for Leon, Guanajuato, Mexico.

Parameter	Value	Units
$\boldsymbol{\xi}$	2.722	Thousands of Pesos /1 million m^3/m
$\overline{\boldsymbol{X}}$	550	Meters
$\boldsymbol{\alpha}$	0.95238095	-
$\boldsymbol{g}$	490.39	$Pesos/$m^3$
$\boldsymbol{k}$	85.81	$Pesos/$m^3$
$\boldsymbol{\beta_{dp}}$	0.2	-
$\boldsymbol{\beta_{sw}}$	0.3	-
$\boldsymbol{q_{sw}}$	1.43	Million m^3
$\boldsymbol{A}$	7.07	Million m^3
$\boldsymbol{\gamma}$	[0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]	-
S	0.13	-
R	1.56	Million m^3/year
Max depth	-126	Meters

Source: Comisión Nacional del Agua (2009, 2011), Muñoz et al (2006).

Table 1B: Parameters used in simulations for Kern County, California.

Parameter	Value	Units
$\boldsymbol{\xi}$	0.13	$USD/ Acre-feet/foot
$\overline{\boldsymbol{X}}$	385	Feet
$\boldsymbol{\alpha}$	0.95238095	-
$\boldsymbol{g}$	146.9	$USD/acre-feet
$\boldsymbol{k}$	27.66	$USD/acre-feet^2
$\boldsymbol{\beta_{dp}}$	0.2	-
$\boldsymbol{\beta_{sw}}$	0.3	-
$\boldsymbol{q_{sw}}$	1.9	Million Acre-feet
$\boldsymbol{A}$	1.29	Million acres
$\boldsymbol{\gamma}$	[0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1]	-
S	0.13	-
R	0.052	Million Acre-feet/year
Max depth	-233	Feet

Source: Feinerman and Knapp (1983)

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