Two are Better than One: A Hybrid Policy that Integrates Water Prices and Quotas Reinforces the Robustness of Both Instruments Against Lobbying

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Many regions worldwide have replaced quotas, as a means to controlling irrigation-water usage, with a hybrid policy that integrates private quotas and uniform prices. This paper characterizes the political equilibrium in a game in which farmers lobby for lower prices and larger quotas. We show that combining the two instruments reinforces the robustness of each against political distortion; consequently, a hybrid policy that follows a quotas-only regime reduces water usage. However, the social welfare rank of the hybrid policy versus the quotas-only and price-only counterparts is an empirical question. We use the equilibrium conditions to derive a structural discrete/continuous choice model that enables estimating the agricultural sector's lobbying power and the level of political organization used to reduce prices. We employ the model to data from Israel during the 1980s; during that period, quotas were set at a village-specific level and prices were set at a region-specific level, thereby generating the variability required to estimate the model's parameters. We obtain empirical support for the reinforcement hypothesis and evidence of strong political influence, but also evidence of considerable free-riding regarding price reduction. Simulations of political equilibria under the quotas-only, price-only and hybrid regimes indicate a domination of the latter in terms of social welfare.

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Key Points:

- We characterize the political equilibrium under a hybrid policy that integrates quotas and a price and conduct an empirical analysis.
- We use the equilibrium conditions to show that a hybrid policy that follows a quotas-only regime reduces water usage.
- We show analytically and empirically that the hybrid policy reinforces the robustness of prices and quotas against political distortion.

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Abstract

Many regions worldwide have replaced quotas, as a means to controlling irrigation-water usage, with a hybrid policy that integrates private quotas and uniform prices. This paper characterizes the political equilibrium in a game in which farmers lobby for lower prices and larger quotas. We show that combining the two instruments reinforces the robustness of each against political distortion; consequently, a hybrid policy that follows a quotas-only regime reduces water usage. However, the social welfare rank of the hybrid policy versus the quotas-only and price-only counterparts is an empirical question. We use the equilibrium conditions to derive a structural discrete/continuous choice model that enables estimating the agricultural sector's lobbying power and the level of political organization used to reduce prices. We employ the model to data from Israel during the 1980s; during that period, quotas were set at a village-specific level and prices were set at a region-specific level, thereby generating the variability required to estimate the model's parameters. We obtain empirical support for the reinforcement hypothesis and evidence of strong political influence, but also evidence of considerable free-riding regarding price reduction. Simulations of political equilibria under the quotas-only, price-only and hybrid regimes indicate a domination of the latter in terms of social welfare.

Key words: Irrigation, Water Pricing, Political Economy, Structural Estimation

JEL classification: D72, Q15

And if one prevail against him, two shall withstand him

Ecclesiastes 4:12, KJV

1. Introduction

Irrigation-water consumption—amounting to 70% of global freshwater usage—is associated with external effects and natural monopolies, both of which economically warrant government intervention. Historically, water quotas and non-volumetric charges have been the common policies to control water usage, but since the 1990s water pricing, promoted by international organizations such as the world bank and the OECD, has become a popular rationing tool worldwide (Dinar et al. 2015). In many regions, prices have been added to the customary quantitative regulations to create a hybrid policy, which integrates administrative prices and quotas; examples of this integration can be found in Australia, California, China, Iran, Israel, Peru, and Spain (Molle 2009, OECD 2010). Nevertheless, governmental intervention incentivizes interest groups to exert political power in order to bend policies to their own private benefits; this exertion may lead to an overuse of water resources (Rausser and Zusman 1991, 1992; Zusman 1997) and to deadweight loss. In the last four decades, there has been a succession of studies on environmental and resource regulation by taxes and quotas under political lobbying; examples include Buchanan and Tullock (1975), Finkelshtain and Kislev (1997), Fredriksson (1997), Aidt (1998), Aidt and Dutta (2004), Finkelshtain and Kislev (2004), Yu (2005), Roelfsema (2007), Miyamoto (2014), Lappi (2017) and MacKenzie (2017). However, to our knowledge, a political equilibrium under a hybrid policy of direct and indirect controls has never been formally characterized (Hepburn 2006). Consequently, the literature lacks an answer to the question of which of the policies is more resistant to the detrimental effects of lobbying in terms of inefficient water usage: prices-only, quotas-only, or a hybrid of prices and quotas?

The contribution of this paper to the literature on the political economy of resource regulations in general, and irrigation-water control in particular, is both theoretical and empirical. Our theoretical model generalizes that of Finkelshtain and Kislev (1997, hereafter FK), who treat quotas and prices as separate, exclusive controls over the usage of a scarce resource and characterize the political equilibrium conditions for each instrument. FK identify two factors that determine the rank of the two instruments in terms of social welfare: the elasticity of the demand of the resource and the level of free-riding associated with the political organization of users for the purpose of collectively lobbying towards the lowering of regionally uniform prices. Evidently, prices dominate quotas if the demand elasticity is sufficiently large relative to the level of political organization for price reduction. We extend FK's framework by modeling an economy in which the two controls are integrated. In addition, we allow for heterogeneity across the resource users with respect to the marginal supply costs of the resource, and show that that heterogeneity constitutes a necessary condition for the emergence of a political equilibrium under which both quotas and prices are effective controls of resource usage. Moreover, the supply heterogeneity is an additional factor that affects the social rank of the instruments, because it provides an advantage to specific quotas over uniform prices in terms of efficiency (unlike uniform prices, individual quotas can be adjusted to equalize the resource's value of marginal product (VMP) of each user to the user's specific marginal supply cost).

While our framework is flexible enough to model various forms of political games and pricing schemes, we follow a two-stage regulation setup, as employed in our empirical case study of irrigation-water control in Israel: first, a regionally uniform water price is set, and in the next stage, user-specific quotas are determined. We characterize the conditions for a political equilibrium in which the two integrated instruments are effective, and therefore they separate the population of farmers into two groups of water users; the consumption of each group is constrained by a different instrument. We show that the lobbying incentives of the two groups are entwined: the larger the first-stage equilibrium regional price, the lower the second-stage users' incentives to lobby for larger private quotas. At the same time, the return from lobbying towards the reduction of the water price is proportional to the total water usage in the region. Therefore, the stricter the second-stage equilibrium quota allocation, the less intensive the first-stage political struggle to lower the price by the users, who foresee the second-stage equilibrium. Accordingly, the model captures the intertwined effects of the interest groups' activities with respect to the price and quotas; activities that reinforce the robustness of both instruments against political distortions. We show that, compared to a quotas-only regime, the hybrid regime reduces the utilization of the scarce water resource and elevates its VMP. Thus, the presence of prices (even as a means to partly covering supply costs rather than controlling consumption) can enhance the effectiveness of quotas. However, the social rank of the hybrid policy versus the quotas-only and price-only counterparts is not unequivocal, and is therefore an empirical question.

There are numerous empirical studies that document lobbying in the context of environmental and resource regulations (Oates 2003); however, empirical studies that test the political-economy theory and/or estimate its structural parameters are scarce. Notable exceptions to that scarcity are Fredriksson and Svensson (2003), who study the impact of political corruption and instability on policy formation, and test the theory in the context of environmental policies, and List and Sturm (2006), who show that electoral incentives influence the stringency of environmental policies. In this paper, in addition to testing the theory by estimating the principal parameters of our political economy model, we also quantify the impact of lobbying on economic welfare. In particular, we show that the political equilibrium conditions associated with the hybrid regime yield structural equations that enable estimating the fundamental parameters of the model by applying a maximum-likelihood procedure based on the discrete/continuous choice (DCC) approach. The DCC model of piecewise linear budget constraints (see Burtless and Hausman 1978 and Mofitt 1986) has been employed for estimating water demand functions, by using observations of water usage under increasing block-rate pricing (e.g., Hewitt and Hanemann 1995; Bar-Shira, Finkelshtain and Simhon 2006; Dahan and Nisan 2007; Finkelshtain, Kan and Rapaport-Rom 2020). In our case, however, the observed quotas and prices, of their own accord, are endogenous variables because they are set in a political game. Consequently, in addition to the demand function, the DCC model incorporates a system of structural political equilibrium equations, and thereby enables the identification of the political influence of the regulated sector, as well as the level of free-riding associated with the cooperative lobbying efforts to lower the uniform price. The estimated structural equations enable conducting simulations of a political equilibrium of prices and quotas under the price-only, quotas-only and hybrid regimes, and comparing the relative robustness of these regimes to political distortion.

An estimation of the model's parameters requires a variability of both quotas and prices. We therefore apply the empirical analysis to data on the usage of irrigation water in the Israeli agricultural sector during the late 1980s; during that period, in addition to village-specific water quotas, water prices were specified to different regions. Our estimation results reveal a sizable and statistically significant negative relation between village-level quotas and regional prices, and thereby provide empirical evidence to the theoretically predicted reinforcement effect of the two integrated instruments on the mitigation of political distortion. By using the DCC structural framework, we estimate the weight assigned by policymakers to political support at 31% and the welfare of the society as a whole at 69%. This finding indicates a small reduction in the political power of the Israeli agricultural sector in the 1980s compared to its influence in the 1960s; Zusman and Amiad (1977) estimated the latter at 40–60%. Concomitantly, we estimate the level of regional political organization for lobbying toward lowering regional prices at only 16%; a level that points at the presence of considerable free-riding. We then use the estimated political parameters and the coefficients of the water-demand function to simulate political equilibria under the three alternative regimes (hybrid, quotas only, and a price only), and evaluate the deadweight loss entailed by lobbying under each regime. We find the hybrid policy socially desirable; the deadweight loss under the quotas-only and price-only policies is about 50% and 110% larger than that of the hybrid, respectively. Finally, we show that, despite the large free-riding regarding lobbying for price reduction, the quotas-only regime dominates the price-only regime because of the combined impacts of the low elasticity of water demand and the large heterogeneity of marginal supply costs.

The following section presents the theoretical model and characterizes the conditions for a political equilibrium. Section 3 presents an institutional description of the Israeli water economy and the features that facilitate the empirical application of the theoretical model to that case study. In Section 4, the conditions for a political equilibrium are employed to form the system of structural equations that is used to estimate the water-demand functions and the political parameters of the model.

Section 5 presents welfare analyses based on simulations of alternative regimes. Section 6 summarizes the paper, and discusses some limitations and potential extensions of the analyses. Appendices A–G provide technical details.

2. Theory

2.1 The Economy

Consider a small open regional economy with $N > 1$ heterogeneous, water-using farms. Let the profit of farm *i*, $i \in N = \{1, \ldots N\}$, be given by $y^i = \pi^i(w^i) - p w^i$, in which w^i is the farm's water usage and $p \in [\underline{p}, \bar{p}]$ is a regionally-uniform agricultural water price, administratively determined by the government. The gross-profit function, $\pi^i(w^i)$, subsumes the prices of all of the variable outputs and inputs, excluding the water expense $p w^i$, and is assumed to be continuous, increasing, strictly concave and twice differentiable. The derivative of $\pi^i(w^i)$ with respect to w^i is the water's VMP, $\pi_w^i(w^i)$; the inverse of this function, $D^i(p) = \pi_w^{i\,-1}(p)$, is the farm's water demand. However, in addition to the regional water price, the government regulates water consumption via farm-level non-tradeable quotas. The water quota allocated to farm *i* is $q^i \in [\underline{q}^i, \bar{q}^i]$, and the farm's water usage is then equal to $w^i = min(D^i(p), q^i)$. We denote by $w \in R^N$ and $q \in [\underline{q}, \bar{q}]$, respectively, the vectors of the water-usage quantities and the quotas of the region's N farms. Our analysis focuses on a set of hybrid controls $\{p, q\}$, which separates the region's N farms into two subgroups; the price binds the water usage of some farms, for which $D^i(p) < q^i$, whereas the farm specific quotas bind the consumption of the other farms.

The cost of providing water, which encompasses delivery costs and scarcity rents, is given by $c(w)$, and is assumed to be increasing in relation to water usage, convex and twice differentiable; we denote the marginal cost by $c_{w^i} \equiv \frac{\partial c(w)}{\partial w^i}$, $c_{w^i} \in [\underline{c}_w, \overline{c}_w] \forall i \in N$. We analyze the short-run water management, in the sense that the number of farms is predetermined and the infrastructure of water supply is in place.

<u>Optimal Hybrid Policy and the Incentives to Lobbying</u>

Because the economy is small and open, the social welfare function $S(w)$, in our case, equals the sum of the agricultural producers' gross profits minus the water-supply cost:

$$S(w) = \sum_{i=1}^{N} \pi^i(w^i) - c(w). \tag{1}$$

Denoting any socially optimal levels by the superscript o, $w^o = \underset{w}{argmax}\, S(w)$ is the vector of water allocations that maximize social welfare, thereby satisfying the equality between the water VMP and marginal supply cost, $\pi_w^i(w_i^o) = c_{w^i} \forall i \in N$, in which w_i^o is the ith element of w^o. In the case that the marginal costs are heterogeneous, a uniform price, by itself, cannot achieve the first best solution, in the sense that the VMPs of all farms equal to the uniform price and not necessarily to their marginal costs. Thus, in a set of hybrid controls (denoted by the superscript h) that is optimal $\{p^{ho}, q^{ho}\}$ and separating, the price p^{ho} is equal to the lowest marginal cost in the region ($\underline{c}_{w^i}$), and the quota of every other farm satisfies $q_i^o = w_i^o = \pi_w^{i\,-1}(c_{w^i})$.

Figure 1 illustrates an optimal separating hybrid policy for a region with only two farms ($i=1,2$) whose marginal costs differ so that $c_{w^2} > c_{w^1}$. The optimal quota assigned to farm 1, q_1^{ho}, is indeterminable except for the fact that it must be sufficiently large to become ineffective, thereby ensuring the effectiveness of the price; that is,

$q_1^{ho} > \pi_w^{1\,-1}\left(c_{w^1}\right)$. The ineffectiveness of q_1^{ho} means that, under the optimal policy, farm 1 has no incentive to lobby for quota enlargement. On the other hand, farm 2 is bound by its quota ($q_2^{ho} = \pi_w^{2\,-1}\left(c_{w^2}\right)$), and therefore its marginal benefit from quota enlargement equals $\pi_w^2\left(q_2^{ho}\right) - p^{ho}$, which implies that if the price p^{ho} increases, then it reduces farm-2's gain from lobbying for an enlargement of its quota q_2^{ho}. At the same time, both farms are motivated to lobby for a lower uniform water price, and their gain from a marginal price reduction equals the total water usage in the region $w_1^{ho} + q_2^{ho}$. Consequently, the lower the water usage in the region is, the lower the motivation to exert political pressure to lower the price is, and therefore a smaller level of the quota q_2^{ho} discourages lobbying. Thus, the price p^{ho} and the quota q_2^{ho} reinforce each other's resistance to lobbying pressures; as will be shown, this feature plays an important role in shaping the levels of the hybrid instruments under an equilibrium in the political game.

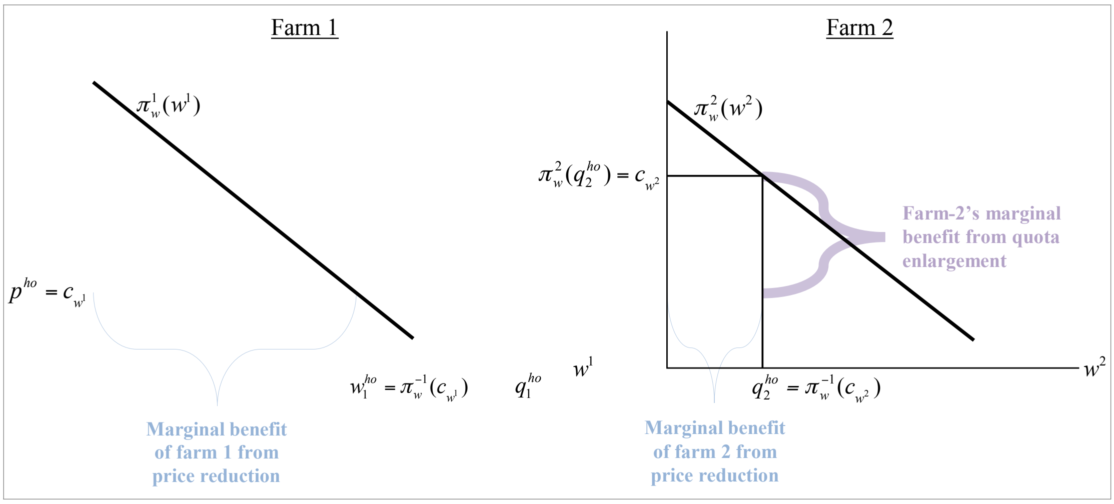

Figure 1 – An optimal separating hybrid policy in a two-farms region with heterogeneous marginal costs.

2.2 Regulation under Lobbying

The uniform price p and the vector of allocated quotas$q$ are set through a political process in which politicians may bend policies in favor of interest groups, who, in return, provide the politicians with political support. Farm-i's investment in lobbying for a larger individual quota is denoted r_i^q. In addition, the farm may contribute r_i^p to a regional lobby that negotiates the region's water price; therefore, the farm's profit, net of political contributions, is $y^i - r_i^p - r_i^q$. Quotas are farm-specific; therefore, free riding regarding lobbying for larger quotas is improbable, and consequently all of the farms that are bound by their water quotas negotiate those quotas. On the other hand, while every farm in the region has an interest to lower the uniform price, the political pressure exercised by the regional lobby acts as a public-good service by benefitting all of the farms, and therefore triggers free-riding. Indeed, several studies (e.g., Bombardini 2008, Furusawa and Konishi 2011 and Gawande and Magee 2012) present theoretical support and empirical evidence for the presence of free-riding regarding lobbying towards common interests. While endogenizing the lobby formation is beyond the scope of this paper, we account for free-riding by letting a subset L $(L \subseteq N)$ of L $(L \leq N)$ farms form the political lobby that pursues the lowering of the uniform price. Thus, the contribution of the regional lobby is $r^p = \sum_{i \in L} r_i^p$, which is to be determined by the equilibrium in the political game described below (the equilibrium conditions determine r^p, but not the farm-specific contribution r_i^p for all $i \in L$; we assume that the contribution of the regional lobby r^p is allocated across the L contributing farms based on some rule that is known to all players; e.g., a fixed payment per acre of cultivated land).

The government's objective function, G, depends on the economy's social welfare $S(w)$ and the aggregate contributions of the campaign $r = r^p + \sum_{i \in N} r_i^q$:

$$G = \alpha r + S(w), \qquad (2)$$

in which $\alpha \geq 0$ is the weight attached by the government to political rewards relative to social welfare $S(w)$; thus, the politicians' preferences can be presented as two weights: political support, $\frac{\alpha}{1+\alpha}$, and social welfare, $\frac{1}{1+\alpha}$.

Our political-economy model draws on the menu-auction game under complete information described by Bernheim and Whinston (1986) and Grossman and Helpman (1994) (hereafter BW and GH, respectively). In line with the practice in Israel, prices are set before quotas are announced; we therefore extend the above authors' framework to a two-stage game. The first stage is a menu-auction game that encompasses a single regional lobby that negotiates the regional water price with the government. In the second stage, N lobbies, each of which represents a specific water user (farm), simultaneously negotiate their individual quotas with the government. The levels of the controls at each stage constitute a perfect Nash equilibrium policy. While the instruments are uniquely determined by the perfect Nash equilibrium in both stages of the game (Proposition 1 of GH), the political reward functions under an equilibrium may take alternative forms and induce different net payoffs to the farmers and politicians. We follow BW and GH and refine the equilibrium by selecting truthful equilibria, which were shown by BW to have the attractive property of being coalition-proof, and ensure a unique equilibrium under reasonable assumptions. To characterize the equilibrium, we employ a backward induction. We first characterize the equilibrium quotas and the associated political rewards determined in the second-stage quota game, all of which are computed for any level of the price, p, and any reward, $r_i^p \, \forall i \in L$, chosen in the first stage. Then, we characterize the equilibrium condition with respect to the price; the equilibrium condition accounts for the price's impact on the equilibrium quotas in the second stage, which are assumed to be anticipated by all players in the first stage.

<u>2.3 The Second Stage: Quota Game</u>

Our political game involves two types of farm-specific quotas. The first type is the historical quota, denoted $\breve{q}_i$ for all $i \in N$; we denote by $\breve{q}$ the vector of historical quota-allocations to farms, which is known to all players. The second type is the equilibrium-quota rule determined by an equilibrium in the political game involving farm *i* and the government under the hybrid policy. Denoting the hybrid equilibrium by superscript *he*, the equilibrium-quota rule $q_i^{he}(p)$ depends on the price p, which is given in the first stage. Under separating hybrid policies, the set of farms with binding equilibrium quotas is given by $Q \equiv \{ i \in N : max(\breve{q}_i, q_i^{he}(p)) \leq D_i(p) \}$, $Q \subseteq N$. Given $\breve{q}$ and p, the government identifies the group of quota-bound farms Q, and picks the specific socially-optimal quota $q_i^{ho} = \pi_w^{i^{-1}}(c_{w^i})$ for each farm, unless the farm donates positive political rewards r_i^q; thus, q_i^{ho} is the threat point for any quota-bound farm in the political game, and thereby it incentivizes political payments. The equilibrium quota, denoted q_i^{he}, equals the equilibrium-quota rule $q_i^{he}(p)$ for each farm *i* from the quota-bound group Q. On the other hand, the water usage is smaller than both the historical and the equilibrium-quota rule for each price-bound farm $i \notin Q$.

The extensive form of the quota game is as follows: first, each water user with a binding quota presents a contribution schedule, which is a function of the vector of quotas q, to the government. Second, the government chooses a vector of quotas q that maximizes its objective function, and then collects contributions from each farm. The equilibrium conditions of the game are identical to those described by Proposition 1 of GH. We adopt GH's assumption that the contribution schedules are locally differentiable around the equilibrium contributions and are therefore locally truthful; this assumption yields the following quota-allocation rule (see proof in Appendix A):

Proposition 1 *If the farms' contribution schedules are differentiable around the equilibrium, then the equilibrium quota q_i^{he} for each farm that is bound by its quota satisfies:*

$$\frac{c_{w^i}+\alpha p}{1+\alpha}=\pi_w^i\left(q_i^{he}\right)\forall i\in Q. \tag{3}$$

The allocation rule in Eq. (3) implies that the political process yields an efficient intra-group water usage, which equates the VMPs of all the farms with binding quotas and with identical marginal costs. Moreover, according to Eq. (3), $c_{w^i}=\pi_w^i\left(q_i^{he}\right)+\alpha\left(\pi_w^i\left(q_i^{he}\right)-p\right)$ for all $i\in Q$; because farms with binding quotas are characterized by $\pi_w^i\left(q_i^{he}\right)>p$, if $\alpha>0$, then $\pi_w^i\left(q_i^{he}\right)<c_{w^i}$ for all $i\in Q$. This inequality implies the existence of welfare loss.

Because $\pi_w^i(\cdot)$ is monotonic, the quota rule defined by Eq. (3) can be written explicitly as

$$q_i^{he}(p)=\pi_w^{i\;-1}\left(\frac{c_{w^i}+\alpha p}{1+\alpha}\right)\forall i\in Q, \tag{4}$$

which, together with the demand function, is used in the empirical analysis below to estimate α.

Intriguingly, Eq. (4) generates a pseudo-political demand equation, in which the equilibrium quota decreases with the rise of the predetermined water price. This result corresponds with the intuitive conclusion derived from Figure 2: the presence of the price reinforces the robustness of the quotas to the distorting impact of political pressures, thereby leading to tightened equilibrium quotas. Moreover, the marginal benefit of a quota-bound farm from a quota enlargement, $\frac{c_{w^i}+\alpha p}{1+\alpha}-p\,\forall i\in Q$, becomes lower as the price rises ($\partial\left(\frac{c_{w^i}+\alpha p}{1+\alpha}-p\right)/\partial p=\frac{-1}{1+\alpha}$). Our empirical results (see Section 5) suggest that the elasticity of the water quotas with respect to the administrative price is -0.27, and therefore we obtain that the hybrid regime in the Israeli water economy creates considerable welfare benefits in comparison with a quotas-only regime.

The characterization of the set of equilibrium-quota rules, denoted $q^{he}(p)$, relies on the differentiability of the schedules of contribution, which yields locally-truthful schedules. As already noted, if the stronger condition of globally-truthful schedules is assumed, the uniqueness of the equilibrium contributions $r_i^q\left(q^{he}(p)\right)\forall i\in Q$ is proven (see Appendix B). Hereafter, we assume that the set of political equilibrium quotas and political contributions $\left\{q_i^{he}(p), r_i^q\left(q^{he}(p)\right)\right\}$ for all $i\in Q$ is unique. Therefore, the impact of the price p on the water consumption and quota of each farm $i\in N$ at the second-stage quota game is predictable at the first-stage price game by all of the players.

2.4 The First Stage: Price Game

In Israel and other countries farmers establish regional organizations to coordinate the provision of a variety of local public goods, such as marketing, research, advertisement, and the organized procurement of farming inputs. Farmers tend to use the same organizations to promote various common local interests, such as lowered water prices. Nevertheless, the level of organization may be incomplete (as we show in the empirical section of the paper, in which we use the equilibrium conditions to estimate the extent of free-riding in the case of Israel).

Given the unique second-stage set of equilibrium-quota rules and contributions, $\{q_i^{he}(p), r_i^q(q^{he}(p))\}\ \forall\, i \in Q$, which is foreseen by all of the players in the first stage, the objective function of the regional lobby (denoted Y) is:

$$Y = \sum_{i \in L} \{y^i(p, q_i^{he}(p)) - r_i^q(q^{he}(p))\} - r^p(p) \tag{5}$$

(recall that the subset L of farms that contribute to the regional lobby to pursue a lower water price may also include farms from the subset of quota-bound farms Q), and the government's objective function is:

$$G = \alpha \left[\sum_{i=1}^{N} r_i^q(q^{he}(p)) + r^p(p) \right] + S(w(p, q^{he}(p))). \tag{6}$$

The equilibrium price, denoted p^{he}, is characterized as follows (see proof in Appendix C):

Proposition 2 *If the farms' contribution schedules are differentiable around the equilibrium, then the equilibrium price* p^{he} *satisfies:*

$$\sum_{i \notin Q} (p^{he} - c_{w^i}) D_p^i = \alpha \sum_{i \in L} w^i = \alpha\phi \left[\sum_{i \in Q} q_i^{he}(p^{he}) + \sum_{i \notin Q} D^i(p^{he}) \right], \tag{7}$$

in which $\phi \equiv \sum_{i \in L} w^i / \sum_{i \in N} w^i$ is the share of the members of the regional lobby in the aggregate regional water consumption, and represents the "regionally organized water" in the price game.

Recall that our analysis presumes the existence of a set of a price and quotas that constitutes a political equilibrium $\{p^{he}, q^{he}(p^{he})\}$; these instruments separate the regional farms into price-bound and quota-bound groups. That is, given the historical quotas $\breve{q}$ and the political equilibrium price p^{he}, the set of quota-bound farms $Q \equiv \left\{ i \in N : max\left(\breve{q}_i, q_i^{he}\left(p^{he}\right)\right) \leq D_i\left(p^{he}\right)\right\}$ satisfies $N \supseteq Q \neq \varnothing$. Appendix D characterizes the sufficient conditions for the existence of a separating equilibrium.

Eq. (7) has a simple, intuitive interpretation. The left-hand side is the price-change's marginal effect on social welfare. On the right-hand side, the aggregate water usage of the members of the regional lobby is the price-change's marginal effect on the members' welfare. In an equilibrium, the first term equals α times the second term.

Worth noting is the dependence of the equilibrium price in the first-stage on the (foreseen) equilibrium quotas determined in the second stage. Larger equilibrium quotas in the second stage (which are, for example, due to larger inverse-VMP functions $\pi_w^{i\,-1}(\cdot)$) incentivize the regional lobby to struggle more intensely to lower the price p^{he} (i.e., the R.H.S of Eq. (7) is larger), which enlarges the aggregate marginal deadweight loss associated with the water price $\sum_{i \notin Q}\left(p^{he} - c_{w^i}\right)$ (i.e., the L.H.S of Eq. (7)). This reflects the intuition, discussed in relation to Figure 1, that the presence of effective quotas in a separating hybrid regime reinforces the robustness of the price to political pressures.

Denoting by s^i the share of farm i in the aggregate water consumption and by η^i its demand elasticity, we may rewrite Eq. (7) as:

$$\sum_{i \notin Q} \frac{\left(p^{he} - c_{w^i}\right)}{p^{he}} s^i \eta^i = \alpha\phi \Longleftrightarrow$$

$$p^{he} = \sum_{i \notin Q} c_{w^i} \frac{s^i\left|\eta^i\right|}{\sum_{i \notin Q}\left(s^i\left|\eta^i\right|\right) + \alpha\phi} \tag{8}$$

(recall that $\eta^i = 0 \,\forall\, i \in Q$). To comprehend Eq. (8), it is useful to consider the socially optimal price under a price-only regime (denoted p^{po}), which is given by

$p^{po} = \sum_{i \in N} c_{w^i} \frac{s^i|\eta^i|}{\sum_{i \in N} s^i|\eta^i|}$. That is, the optimal price, operating as a single control, equals the weighted average of the marginal costs of all of the regions' farms, in which the weights comprise the products of the farms' consumption shares and the demand elasticities. Therefore, an optimal uniform price under a price-only regime does not achieve the first-best water allocation (that equates marginal costs to VMPs), but rather yields the second-best optimum. The equilibrium price under the hybrid-policy, given by Eq. (8), preserves this second-best principle, but creates an additional welfare loss through the political influences reflected by the product of α and ϕ.

As we have already noted, the empirical section employs Eq. (4) to identify the parameter α. Combining Eqs. (7) and (4) enables us to also identify the parameter ϕ, and thereby to compute the extent of free-riding in the region with respect to lobbying for price reduction: $1-\phi$.

2.5 Hybrid vs. Quotas-Only Regimes

As we have mentioned earlier, hybrid water-control instruments have gained popularity in recent decades and have replaced, in many places, the use of quotas-only regimes. In this subsection, we use the characterization of the hybrid equilibrium (Eqs. 3 and 7) to examine the implications of this "constitutional" reform on welfare.

Suppose that only quotas regulate the water economy (i.e., $p=0$). Then, according to Eq. (4), the quotas under a political equilibrium (in this case denoted q_i^{qe},

$i \in N$) are given by the quota allocation rule $q_i^{qe} = \pi_w^{i\;-1}\left(\frac{c_{w^i}}{1+\alpha}\right) \forall i \in N$. Now assume that a price is introduced in addition to the quotas, and therefore that a hybrid-policy political equilibrium emerges, wherein the quotas-only political-equilibrium allotments constitute the historical quotas; formally: $\breve{q}_i = q_i^{qe} \forall i \in N$. Under a hybrid-equilibrium price $p^{he} > 0$, the equilibrium quotas are given by $q_i^{he} = \pi_w^{i\;-1}\left(\frac{c_{w^i} + \alpha\, p^{he}}{1+\alpha}\right)$ $\forall i \in N$, which implies that the historical quotas exceed the hybrid-equilibrium quotas; formally: $\breve{q}_i = q_i^{qe} > q_i^{he}$ for all $i \in N$. Therefore, the set of quota-bound farms Q is dictated only by the historical quotas (i.e., because $\breve{q}_i = q_i^{qe}$ and $max\left(q_i^{qe}, q_i^{he}\left(p^{he}\right)\right) = q_i^{qe}$ for all $i \in N$, the condition $Q \equiv \left\{i \in N : max\left(\breve{q}_i, q_i^{he}\left(p^{he}\right)\right) < D_i\left(p\right)\right\}$ becomes $Q \equiv \left\{i \in N : q_i^{qe} < D_i\left(p\right)\right\}$). Consequently, the set Q includes those farms for which $\frac{c_{w^i}}{1+\alpha} > p^{he}$, and for whom the hybrid-equilibrium VMP, $\frac{c_{w^i} + \alpha\, p^{he}}{1+\alpha}$, exceeds the quotas-only equilibrium VMP, $\frac{c_{w^i}}{1+\alpha}$. Likewise, the VMP of the price-bound farms, p^{he}, exceeds $\frac{c_{w^i}}{1+\alpha}$. Therefore:

Proposition 3 *Under a political equilibrium, a hybrid regime that follows a quotas-only regime increases the VMPs of all water users.*

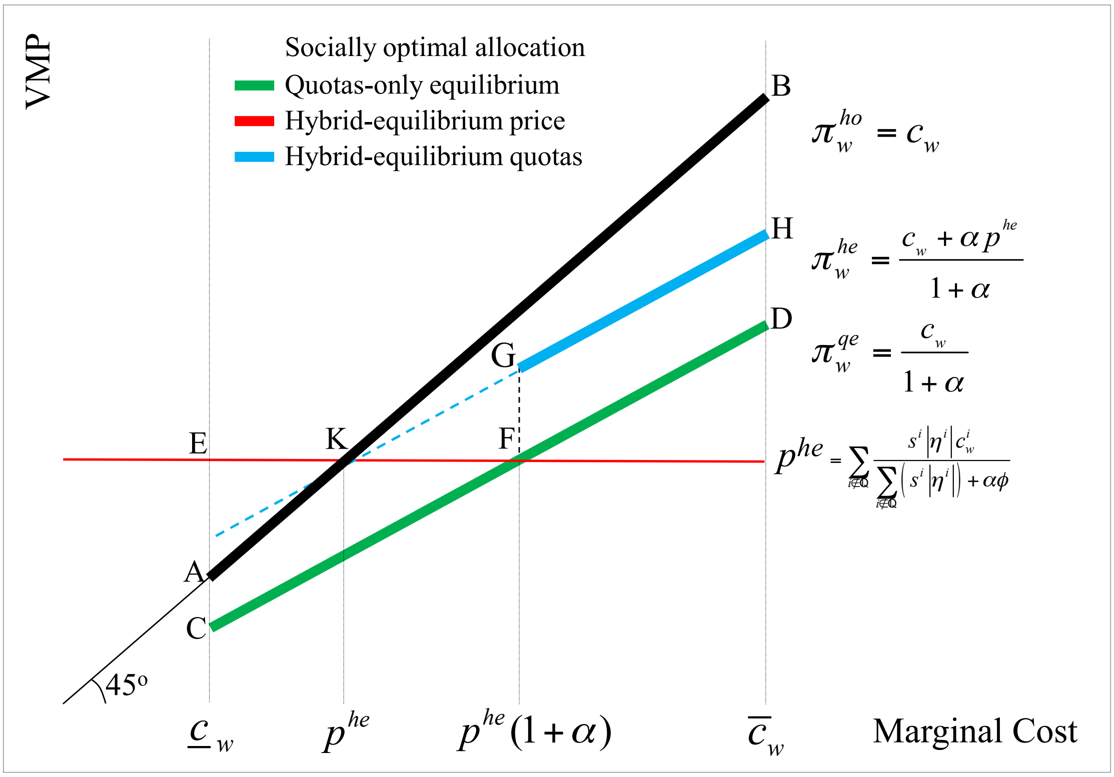

Figure 2 – Schematic VMP curves of the socially optimal solution and political equilibria under the quotas-only and hybrid policies—plotted versus marginal costs.

Figure 2 illustrates the phenomenon expressed by Proposition 3. The horizontal axis represents the farms' marginal costs, distributed in the range $[\underline{c}_w, \bar{c}_w]$. The VMPs of the farms under alternative regimes are depicted as functions of the marginal cost c_w. Starting with the socially optimal allocation, the VMP function under the welfare-maximizing allocation, $\pi_w^{ho} = c_w$, coincides with the 45° line in the segment AB. Under the quotas-only regime, the political equilibrium VMP, denoted π_w^{qe}, equals $\frac{c_w}{1+\alpha}$; it is depicted in Figure 2 by the sloped green segment CD, which lies below the 45^0 line for the entire range of marginal costs $[\underline{c}_w, \bar{c}_w]$ and therefore indicates the presence of welfare loss. Once the administrative uniform price is introduced, a hybrid equilibrium emerges, and yields a non–continuous VMP function: the VMPs of farms with marginal costs in the range $\left[\underline{c}_w, p^{he}(1+\alpha)\right]$ coincide with the equilibrium price $p^{he} = \sum_{i \notin Q} c_{w^i} \frac{s^i |\eta^i|}{\sum_{i \notin Q} \left(s^i |\eta^i|\right) + \alpha\phi}$ along the horizontal red segment EF; farms with marginal costs in the range $\left[p^{he}(1+\alpha), \bar{c}_w\right]$ are bound by their equilibrium quotas, and their VMPs are located on the sloped blue segment GH, which, according to Eq. (3), is given by $\pi_w^{he} = \frac{c_w + \alpha p^{he}}{1+\alpha}$.

Because $\pi_w^{he} \geq \pi_w^{qe}$ for all $c_w \in \left[\underline{c}_w, \bar{c}_w\right]$, the introduction of a price to form the hybrid regime leads to a higher VMP path and a lower level of resource utilization for the quota-bound farms in the marginal cost range $\left[p^{he}(1+\alpha), \bar{c}_w\right]$. Regarding the VMPs of the price-bound farms in the marginal cost range $\left[\underline{c}_w, p^{he}(1+\alpha)\right)$ (segment EF), these VMPs exceed the farms' historical allotments (decided upon under a quotas-only equilibrium), and are lower than the farms' marginal costs. However, for price-bound farms with marginal costs in the range $\left[\underline{c}_w, p^{he}\right)$, the price p^{he} exceeds the marginal cost c_w (as shown by segment EK), and therefore leads to a lower-than-optimal water usage; the associated deadweight loss may exceed that of a quotas-only regime (for the specific minimal marginal cost $\underline{c}_w$ depicted in Figure 2, the inequality $p^{he} - \underline{c}_w > \underline{c}_w - \frac{\underline{c}_w}{1+\alpha}$ implies the relative advantage of the quotas-only regime over the hybrid regime). Thus, a theoretical normative ranking of hybrid and quotas-only regimes is inconclusive, and calls for an empirical analysis.

It is worthy to note that if the quotas-only regime is replaced by a price-only policy, the resultant political equilibrium price (denoted p^{pe}) is given by

$p^{pe}=\sum_{i\in N} c_{w^i}\frac{s^i|\eta^i|}{\sum_{i\in N}\left(s^i|\eta^i|\right)+\alpha\phi}$, which incorporates the marginal costs of all N farms in the region. On the other hand, the price p^{he} incorporates only the marginal costs of the price-bound farms (see Eq. 8), and can be higher or lower than p^{pe}; therefore, the relative social desirability of the hybrid and price-only policies is also an empirical question.

2.6 Comparative Statics Analyses

We analyze the qualitative responses of the price p^{he} and a farm-specific quota q_i^{he} to marginal changes in four exogenous factors: the political parameters α and ϕ, the marginal cost c_{w^i} (hereafter we assume that the marginal costs are constant—see justifications in Section 4), and a shifter of the water demand of the entire agricultural sector (e.g., a technological progress or an improvement in the terms of trade). The effect of the last factor is modeled by the introduction of a parameter v that affects the gross-profit function$\pi^i\left(p^{he},q_i^{he},v\right)$, in which $\pi_v^i\geq 0$ and $\pi_{wv}^i\geq 0$ for all $i\in N$. Table 1 summarizes the results of the comparative statics analyses (see Appendix E for proofs).

Table 1 – Comparative statics analyses with respect to the responses of the price p^{he} and of a farm-specific quota q_i^{he} to changes in α, ϕ, c_{w^i} and in the parameter v (a whole-sector demand shifter).

Parameter	p^{he}	q_i^{he}
α	-	+

ϕ	-	+
c_{w^i}	+	-
v	-	+

The responses of p^{he} and q_i^{he} to marginal increases in α, ϕ and c_{w^i} are intuitive. Note that ϕ has an only indirect impact on the quota; recalling Eq. (3), ϕ's indirect impact is achieved by lowering the price p^{he}, and thereby increasing the quotas. Regarding the parameter v, a marginal increase in v shifts the entire farmer population towards a larger water consumption for a given equilibrium price p^{he} (we assume that the slope of the VMP function is invariant to changes in v: $\pi^i_{wwv}=0$); the rise in water usage leads to an increase in the farmers' marginal gain from a price decrease (R.H.S. of Eq. 7), which in turn increases the motivation to lobby towards quota enlargements (Eq. 3).

In the empirical part of the paper, we test and quantify the effects of the above comparative statics in the Israeli case, and show that the analytical predictions are consistent with the data and economically significant.

3. Israel's Water Polity

Water management in Israel faces three challenges: (1) precipitation is abundant in the north, whereas most of the agricultural areas are located in the dry south; (2) rainfall occurs only during the winter, but irrigation-water usage peaks during the summer; (3) precipitation fluctuates considerably among years, and series of successive drought years are common. To cope with these challenges, Israel has established a complex water-distribution network that connects almost all of the regions of the country. The management of this broad infrastructure system is supported by the Israeli Water Law (1959), inherited from the historical Ottoman and British law systems (Laster and Livney 2008), which assign to the people all of the property rights for water sources and to the government the responsibility over water management. The governmental company Mekorot operates the inter-regional water network, and supplies most of the water to the end users. These institutional settings make Israel's water economy extremely centralized, and therefore it attracts political pressures.

Until the early 1990s, irrigation water in Israel was regulated by village-specific non-tradable annual quotas combined with regionally uniform tariffs, both of which were set by governmental institutions (subject to parliamentary approval), with the Water Commission and the Ministry of Agriculture maintaining dominance over the decision-making process. The fact that quotas were village-specific and prices were regional created a temporal and spatial variability in both prices and quotas, which is required for the empirical estimation of the structural parameters of the political-economy model described above. In practice, prices were set before the rainy season, whereas quotas were announced only after the winter rains were observed and in relation to the water stocks in the reservoirs and to the village-specific historical quotas; accordingly, we formulate our model as a two-stage political game.

Political distortion occurs if incentives to lobbying exist. Since the 1980s, the agricultural sector has utilized, in most years, less water than allowed by the aggregate quota: while some farmers were constrained by their quantitative allocations, others did not fully use the water they were allotted (Kislev and Vaksin 2003). The fact that the two instruments are effective water-usage controls indicates that incentives for political pressure towards both price reduction and the enlargement of quotas exist. In Figure 3, we present regional summaries of freshwater consumptions, quotas, prices and supply costs, all of which are computed according to our sample of 303 villages in 24 water-price regions during the years 1985–1988. Figure 3a shows that in 21 out of the 24 regions some villages did not consume their entire quotas—a finding that indicates the presence of effective hybrid controls. On average, the price binds consumption in 48% of the village-year observations, and the overall regional water consumption amounts to 94% of the aggregate quota. However, in 11 water-price regions, the cumulative consumption exceeds the total regional quota; the excessive water consumption in each of these regions indicates that, under the prevailing prices, a strong motivation for farmers to lobby for quota enlargements exists. The fact that the cumulative consumption exceeds the aggregate quota may also point to possible errors in the measurement and documentation of water consumption and to management, technical and enforcement failures; our econometric analysis controls for such unobserved factors.

An additional condition for effective lobbying is the negotiability of the regulatory instruments. In the early 1960s, each village was allotted a normative quota based on the size of its cultivable land and on other regional factors. These historical allocations are termed "flexible quotas" because they have served as benchmarks for annual quota-allocation adjustments in relation to the national water stock and to additional considerations (Ishay 1991). Regarding price settings, indeed, the Israeli Water Law allows for much flexibility (e.g., water payments can vary according to the purpose of the usage, the consumer's ability to pay, et cetera). In Figure 3b, we compare the uniform price in each region to the regional average water-supply cost, which we separate into energy costs and total costs (all monetary values in the paper are reported in 2020 US dollars). Evidently, the sample-average price is lower than 30% and 50% of the total and energy costs, respectively. In addition, the prices and costs vary across regions; in almost all of the regions, the water price is lower than the total cost, and in 15 regions it even falls short of the energy cost. Apparently, farmers do not bear the full explicit cost of irrigation-freshwater supply.

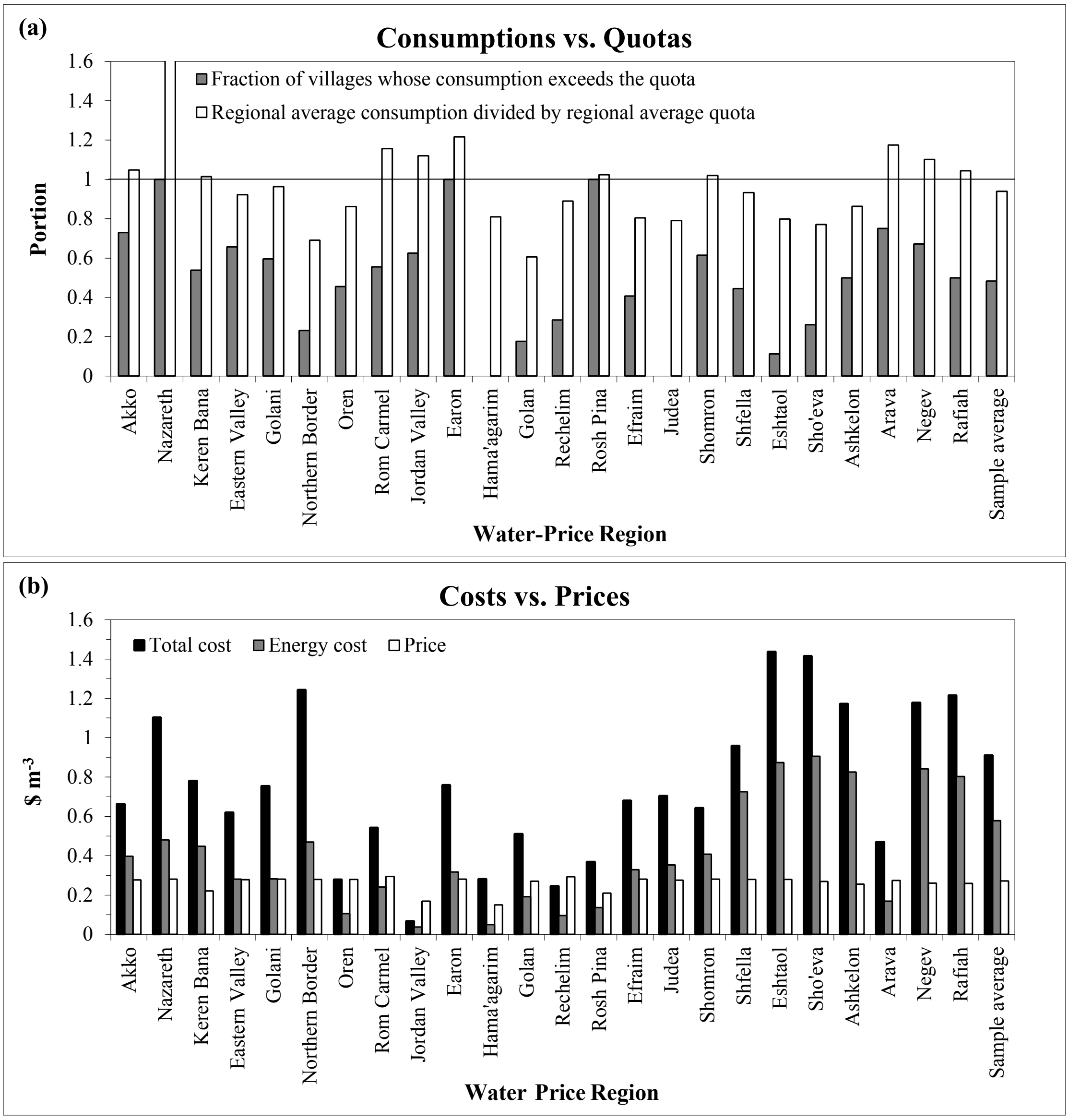

Figure 3 – Regional summaries of (a) freshwater consumptions and quotas, and (b) prices and supply costs; both (a) and (b) are computed according to a sample of 303 villages in 24 water-price regions in Israel during the years 1985–1988. The total costs incorporate energy, capital and operational costs. The energy and total costs are both averages that are weighted by the villages' shares in the regional water usage.

There is ample evidence that the Israeli farming sector is politically well-organized and influential in decision-making forums. Farmers have a notable lobby in the Israeli Parliament, and for many years the water commissioners and the ministers of Agriculture were also farmers, and therefore familiar with the economic implications of water policies on the agricultural sector because of both their own experience and the official master plans of the water economy (Schwartz 2010). Similarly, many of the senior functionaries in the bureaucracy had practiced agriculture, and were often instated by the farming organizations; they had to be attentive to the demands of their fellow farmers with respect to various interests, including water prices and quota allocations (Kislev et al. 1989, Zusman 1997, Plaut 2000, Mizrahi 2004, Feitelson 2005, Kislev 2006, Margoninsky 2006). In addition to lobbying at a national-level, farmers took advantage of municipal and regional cooperatives to promote local interests. Noteworthy anecdotal records of success in the regional scale include the relatively low fees set for water extraction in the northern regions of Israel since the early 1990s (Kislev 2011), and the increase in water allotments to the southern areas in a period of growing water scarcity (Israel Government decision, 2005). Concomitantly, single villages have routinely solicited the bureaucrats at the Water Commission to increase their water allotments (Feinerman, Gadish and Mishaeli 2003).

In this regulatory environment, political contributions were not necessarily made in the form of monetary payments; they included in-kind campaign assistance, demonstrations, and other forms of political support. Therefore, the general idea of political models—political rewards in exchange for the bending of policies in favor of contributing lobbyists—applies in the Israeli water sector as well. Thus, the observed water prices and quotas can be viewed as constituting an equilibrium in a political game, wherein well-informed regulators weigh political contributions against welfare losses.

Given the above features, the case of irrigation-water management in Israel during the 1980s fits our empirical objectives. In addition, the Israeli vegetative agricultural sector is open (Israel Ministry of Agriculture 2001) and small (less than 2% of Israel's GDP), and, within it, changes in the prices of irrigation-water have an insignificant impact on the prices of outputs (Fuchs 2014); therefore, the indirect effect on farmers' income is negligible. All of these features facilitate our analysis, which can be formulated based on a partial equilibrium; that is, when negotiating water policies, both policymakers and farmers in the regional and village levels neglect the indirect general-equilibrium effects on other sectors and products and the potential effects of income distribution associated with the public financing of water-regulation reforms. Furthermore, in relation to FK's modeling framework, it is not uncommon in the Israeli agricultural sector for policy reforms to be framed as revenue-neutral policy shifts, thereby eliminating income effects; for example, in 2017 the Ministry of Finance raised, within the framework of the 27th amendment to the Water Law, the water tariff for farms located in the northern regions of Israel, and simultaneously allocated 530 million NIS to those farms as a form of compensation (Shacham 2017).

4. Structural Estimation of the Model Parameters

In this section we use the equilibrium conditions (4) and (7) to develop a structural econometric framework, which we then employ to the case of Israel in the 1980s to estimate the water demand and the political parameters α and ϕ. We use the results of the estimation to test the qualitative predictions of the theory, and (in the following section) to simulate the political equilibria under alternative regimes and compare the regimes' welfare implications. We estimate the demand function and the quota-allocation rule using data at the village level, and the price-setting equation using data at the regional level.

4.1 Water Demand and Quota-Allocation Functions

Our econometric challenge is to "explain" two observed quantities: per-village water usage and water quota, both of which are endogenous in our model. Recall that (a) water usage is determined by either the price or the quota, and (b) quotas are set through the political process. Consequently, our task is to estimate two structural equations: the water-demand function and the function of the quota-setting rule; the latter incorporates the demand and marginal cost parameters, as well as the political parameter α.

We begin by specifying a linear water-VMP function:

$$\pi_w^i\left(w^{it}, z^{it}\right) = a z^{it} - b w^{it}, \tag{9}$$

in which w^{it} and z^{it} are, respectively, the observed water consumption and a vector of covariates specific to village i at year t; a is a vector of parameters and b is a slope parameter, and both are assumed identical for all i and t. The above specification yields the following linear demand function:

$$D\left(p^{it}, z^{it}\right) = \frac{1}{b}\left(a z^{it} - p^{it}\right), \tag{10}$$

in which p^{it} is the water price, which is identical for villages in the same region but may differ across regions.

Let q^{it} be the observed annual water quota of village i in year t. Substituting the linear VMP specification in Eq. (9) into the equilibrium quota-allocation rule in Eq. (3) yields:

$$\frac{c_w^{it} + \alpha p^{it}}{1+\alpha} = a z^{it} - b q^{it} \; \forall i \in Q, \tag{11}$$

in which c_w^{it} is the village-specific marginal cost. We assume that the village-specific marginal costs are constant with respect to the village's own water consumption and the water consumption of every other village (we return to this assumption in the next section). Thus, the marginal cost is specified as a weighted sum of explicit cost factors and other variables, which might affect the perception of policymakers with respect to the costs of water provision (e.g., the annual natural enrichment of reservoirs). We therefore specify $c_w^{it} = \rho x^{it}$, in which x^{it} is the vector of the cost variables and ρ is the corresponding vector of coefficients. We substitute this formulation into Eq. (11) and rearrange it to obtain a linear equilibrium quota-allocation rule:

$$Q\left(p^{it}, x^{it}, z^{it}\right) = \frac{1}{b} a z^{it} - \frac{1}{b\left(1+\alpha\right)} \rho x^{it} - \frac{\alpha}{b\left(1+\alpha\right)} p^{it} \, \forall i \in Q. \qquad (12)$$

Note that the political parameter α is identifiable through the ratio of the price coefficients in the demand and quota equations (Eqs. 10 and 12).

4.2 Discrete/Continuous Choice Framework

The observed water usage in the sample may be equal either to the quota or to the demand function, and therefore the nature of our model pertains to the Discrete/Continuous Choice framework, suggested by Burtless and Hausman (1978) and Moffitt (1986) and adopted for the estimation of irrigation water demand under tier pricing (e.g., Bar-Shira, Finkelshtain and Simhon 2006). While previous applications of the DCC approach to water usage focused on the estimation of the demand function, our model incorporates both the water demand and the quota-allocation rule as two interrelated equations.

Based on the DCC convention, we employ a linear additive formulation and include three random elements to capture the impact of unobserved factors. The first element stands for technological heterogeneity across villages and time that is not explained by z^{it} and p^{it}; it is represented here by the random variable γ^{it}, which is not observed by the econometrician but is known to the village's farmers and therefore affects their water demand. The two additional sources of randomness are those associated with measurement errors, inaccuracies in the data and optimization mistakes. The random variable ε^{it} represents errors in farmers' decisions on water usage, governmental enforcement faults, and management, measurement, documentation and irrigation technical failures. The random variable u^{it} stands for deviations from the political equilibrium condition and for miscalculations concerning the allocation of quotas by the government. The system of equations of water-demand and quota-allocation rule is:

$$w^{it}=\begin{cases} D\left(p^{it},z^{it}\right)+\gamma^{it}+\varepsilon^{it}\; if\; D\left(p^{it},z^{it}\right)+\gamma^{it}\le q^{it} \\ q^{it}+\varepsilon^{it}\; if\; D\left(p^{it},z^{it}\right)+\gamma^{it}>q^{it}, \end{cases} \tag{13}$$

$$q^{it}=\begin{cases} q^{it-1}+u^{it}\; if\; D\left(p^{it},z^{it}\right)+\gamma^{it}\le q^{it} \\ Q\left(p^{it},x^{it},z^{it}\right)+u^{it}\; if\; D\left(p^{it},z^{it}\right)+\gamma^{it}>q^{it}. \end{cases} \tag{14}$$

As shown by Eq. (13), if the quantity demanded at the given price $D\left(p^{it},z^{it}\right)+\gamma^{it}$ (which includes the stochastic amount associated with the unobserved heterogeneity γ^{it}) does not exceed the quota q^{it}, then consumption is set by the demand function plus the stochastic error term ε^{it}:$w^{it}=D\left(p^{it},z^{it}\right)+\gamma^{it}+\varepsilon^{it}$. If water demand surpasses the quota, then the observed water usage equals the quota plus the error term: $w^{it}=q^{it}+\varepsilon^{it}$. The quota's endogenous formation is formulated in Eq. (14) as follows: if the demand exceeds the observed quota, then the village contributes a positive amount for lobbying, and its allocation is determined by the political quota-setting rule plus the error term: $q^{it}=Q\left(p^{it},x^{it},z^{it}\right)+u^{it}$. However, if the observed quota exceeds the demand, then it is not binding, and therefore the political contributions vanish; in this case we assume that the quota q^{it} equals the quota of the previous year (i.e., the historical quota) plus the error term: $q^{it}=q^{it-1}+u^{it}$.

We estimate Eqs. (13) and (14) by employing a maximum-likelihood procedure. We denote by θ the set of parameters of the functions $D\left(p^{it}, z^{it}\right)$ and $Q\left(p^{it}, x^{it}, z^{it}\right)$ and of the joint density distribution functions of the stochastic variables γ, ε and u. The probability of observing a combination of the water consumption w^{it} and the quota q^{it} is given by the two-element probability function:

$$Pr\left(w^{it}, q^{it} \middle| p^{it}, q^{it-1}, z^{it}, x^{it}, \theta\right) = \text{¿}\, Pr\left[\gamma^{it} + \varepsilon^{it} = w^{it} - D\left(p^{it}, z^{it}\right), \gamma^{it} \leq q^{it} - D\left(p^{it}, z^{it}\right), u^{it} = q^{it} - q^{it-1}\right]$$
$$+ Pr\left[\varepsilon^{it} = w^{it} - q^{it}, \gamma^{it} > q^{it} - D\left(p^{it}, z^{it}\right), u^{it} = q^{it} - Q\left(p^{it}, x^{it}, z^{it}\right)\right].$$

(15)

The associated likelihood function of the sample is

$$L = \prod_i \prod_t Pr\left(w^{it}, q^{it} \middle| p^{it}, q^{it-1}, z^{it}, x^{it}, \theta\right). \tag{16}$$

We assume that the random variables γ, ε and u are statistically independent and normally distributed so that $\gamma \sim N\left(0, \sigma_\gamma^2\right)$, $\varepsilon \sim N\left(0, \sigma_\varepsilon^2\right)$ and $u \sim N\left(0, \sigma_u^2\right)$, and thereby the probability function in Eq. (15) is readily formulated in terms of the standard normal probability density function (see Appendix F).

4.3 The Price-Formation Equation

We estimate the parameters of the price-formation equation at the regional level. Let N_{jt}^p be the number of villages with an effective price in region j in year t, let W_{jt} be the regional aggregate water consumption, and denote region-j's observed water price by p_{jt}. By using the identity $\pi_w^{it} = p_{jt}$ for every price-bound village i in region j and our linear specifications for the demand and cost functions (Eqs. 10 and 12), and with some rearrangements, Eq. (7) becomes:

$$p_{jt} = \xi c_{jt} + \delta \frac{W_{jt}}{N^p_{jt}} + \omega_{jt}, \tag{17}$$

in which c_{jt} is a vector of variables related to the region-level supply costs, ξ is the set of corresponding coefficients, $\delta \equiv b\alpha\phi$ is the parameter through which we identify ϕ, and ω_{jt} is an error term. Because the term $\frac{W_{jt}}{N^p_{jt}}$ may be endogenous, we use as instruments for $\frac{W_{jt}}{N^p_{jt}}$ various exogenous demand shifters (e.g., the precipitation during October and April, amounts that are expected to be negatively correlated with irrigation). We then employ the limited-information maximum-likelihood (LIML) procedure to estimate the model's parameters. Using Eqs. (10), (12) and (17), we identify ϕ by the identity $\phi = \frac{\delta}{\alpha b}$.

4.4 Data and Variables

We estimate the model's parameters using an unbalanced panel of 1,093 observations of irrigation freshwater usage, quotas, prices, and additional village-level covariates spanning the years 1985-1988. The panel encompasses 303 villages from 24 water-price regions. We select village-year observations into the sample based on three criteria. First, in order to avoid a potential dependence of the VMP on the water quality (a dependence that is not simple to control for; see Finkelshtain, Kan and Rapaport-Rom 2020), we include observations that applied only freshwater. Second, we use villages that received their water only from Mekorot, whose end-user prices were set by the government and are therefore available for our analysis. Third, we exclude exceptional small-scale agricultural water users with cultivated areas of less than 50 hectares per village or water quotas of less than 50,000 m³ per year, because such small water users may represent noncommercial activities. The aggregate water usage by the villages in the sample accounts for 20% of the total agricultural freshwater consumption in Israel during the study period.

Table 2 provides descriptive statistics of the variables in the dataset and reports their sources. The data includes the freshwater applications, quotas and prices, as well as the demand- and cost-related variables, which are represented in Eqs. (10) and (12) by the vectors z^{it} and x^{it}. As we have already noted (recall Figure 3a), the per-village average water consumption is lower than the average water quota, and in 48% of the observations the village's quota exceeds the documented consumption—facts that indicate that, for a part of the sample, the price is the effective control. However, this calculation is "naive" because it ignores the impact of random effects. In the next section, we account for the impact of unobserved factors by expressing the effectiveness of the hybrid instruments in terms of probabilities; to do so, we use the estimated probability-density functions of the random variables γ, ε and u.

As noted above, we assume that village-specific marginal supply costs are constant. This assumption is justified on several grounds. First, the assumption is consistent with our explicit-cost dataset and with recent estimations of the cost function of water supply in Israel (Reznik et al. 2016). Second, sectoral stakeholders tend to consider marginal costs as constants (Feinerman, Gadish and Mishaeli 2003). Third, because the water-distribution network connects almost all of the country's regions, changes in the water supply to an individual consumer barely affect the amount of water available to the other consumers (the largest village consumes less than 0.2% of the aggregate water supply), a fact that justifies a linear approximation of a village's impact on the country's water-supply cost. Fourth, water storage in aquifers and surface reservoirs provides the water supply across locales and time-periods with flexibility. The last two features imply that all consumers almost equally share the burden of water scarcity. Therefore, we decompose the supply cost into an element of explicit water-delivery cost that is time-invariant and village specific and an element of implicit water-scarcity cost that is time-varying and uniform across villages; the latter is represented by the annual natural enrichment of reservoirs. Explicit water-delivery costs, separated into energy and capital & operation costs, were detailed by Mekorot's supply facilities; each facility allocates water to a group of adjacent villages based on engineering and topographic considerations. For the estimation of the price-formation equation, we use the village-level explicit costs to compute the average costs for each of the 24 water-price regions.

Table 2 – Descriptive statistics of the dependent and explanatory variables.

Variable	Units	Mean/Frequency	Std. Deviation
Water usage[a]	1000 m^3 $year^{-1}$ $village^{-1}$	951	491
Water quota[a]	1000 m^3 $year^{-1}$ $village^{-1}$	1013	429
Water price[b,c]	\$ m^{-3}	0.275	0.05
Energy cost[b]	\$ m^{-3}	0.575	0.25
Capital & operation cost[b]	\$ m^{-3}	0.35	0.2
Natural enrichment[c]	10^6 m^3 $year^{-1}$	1280	313
October precipitation[d]	mm $month^{-1}$	35.9	26.2
Aprill precipitation[d]	mm $month^{-1}$	22.3	22.5
Annual precipitation[d]	mm $year^{-1}$	526	183
Elevation above sea level	m	183	223
Agricultural land[a]	1000 m^2 $village^{-1}$	2745	2201
Perennials' area[a]	1000 m^2 $village^{-1}$	739	578
Light soil[e]	Dummy	0.46	0.50
Medium soil[e]	Dummy	0.06	0.24
Heavy soil[e]	Dummy	0.48	0.50
North	Dummy	0.37	0.48
Center	Dummy	0.43	0.50
South	Dummy	0.20	0.40

Cooperative (Moshav)	Dummy	0.78	0.41
Communal (Kibbutz)	Dummy	0.18	0.38
Minority	Dummy	0.04	0.20
Agriculture terms of trade[f]	Index (1952=100)	65.2	1.30

a. Ministry of Agricultural & Rural Development. b. Monetary values are reported in 2020 US Dollars. c. Water Commission. d. Meteorological Service of Israel (https://ims.data.gov.il/ims/1). e. Rabikovitz (1992). f. Kislev and Vaksin (2003).

To explain the water demand, we use various topographic, climatologic and institutional attributes of the villages. Finally, the agriculture terms-of-trade index (the price ratio of vegetative agricultural products to farm inputs) serves as a shifter of the water demand of the agricultural sector as a whole (analogous to the parameter v mentioned with respect to the comparative statics analyses).

4.5 Estimation Results

We first describe the results of the estimation of the demand and quota equations (Eqs. 10 and 12) using the DCC maximum likelihood framework. To account for possible heteroskedasticity in the random variable ε, we specify the standard deviation σ_{ε} as a linear function of the village's total agricultural land. In Figure 4, we evaluate the goodness-of-fit of the estimation by comparing the observed and the computed expectation values of the water usage and quota (we calculate the expectation values using a simulation framework, which is based on the estimated likelihood function and presented in detail in the next section). The correlation coefficient of the predicted and observed series is 0.86 for quotas and 0.64 for water consumptions; both coefficients indicate a reasonable fit. While the distribution of the predicted consumption is less dispersed than that of the actual quantities, all other distribution moments are quite similar. In particular, the predicted average water usage and quota are very similar to their observed counterparts (see Figures 4c and 4d).

Table 3 reports the estimated coefficients of the demand and quota functions; we commence with the demand. The estimated standard errors, σ_{γ} and σ_{ε}, indicate that most of the unexplained variation in water consumption is associated with the technological heterogeneity among villages (based on Tables 2 and 3, for the average village we get $\sigma_{\varepsilon} = \exp(4.92 + 0.0016 \times 2{,}745) = 213$ and $\sigma_{\gamma} = \exp(5.82) = 338$). As expected, the price coefficient is negative and significant (we discuss the demand elasticity in the next section). Only a few of the variables exhibit statistically-significant impacts on the water demand; among them are the village's total cultivable land, the area allocated to perennials, which is assumed to be exogenous in the short run, and the terms-of-trade index, which acts as a demand shifter. All of the other estimated coefficients, such as the effects of increased rainfall, a higher elevation above sea level, and a farther south location in the drier areas of the country, show the expected signs, but are statistically insignificant.

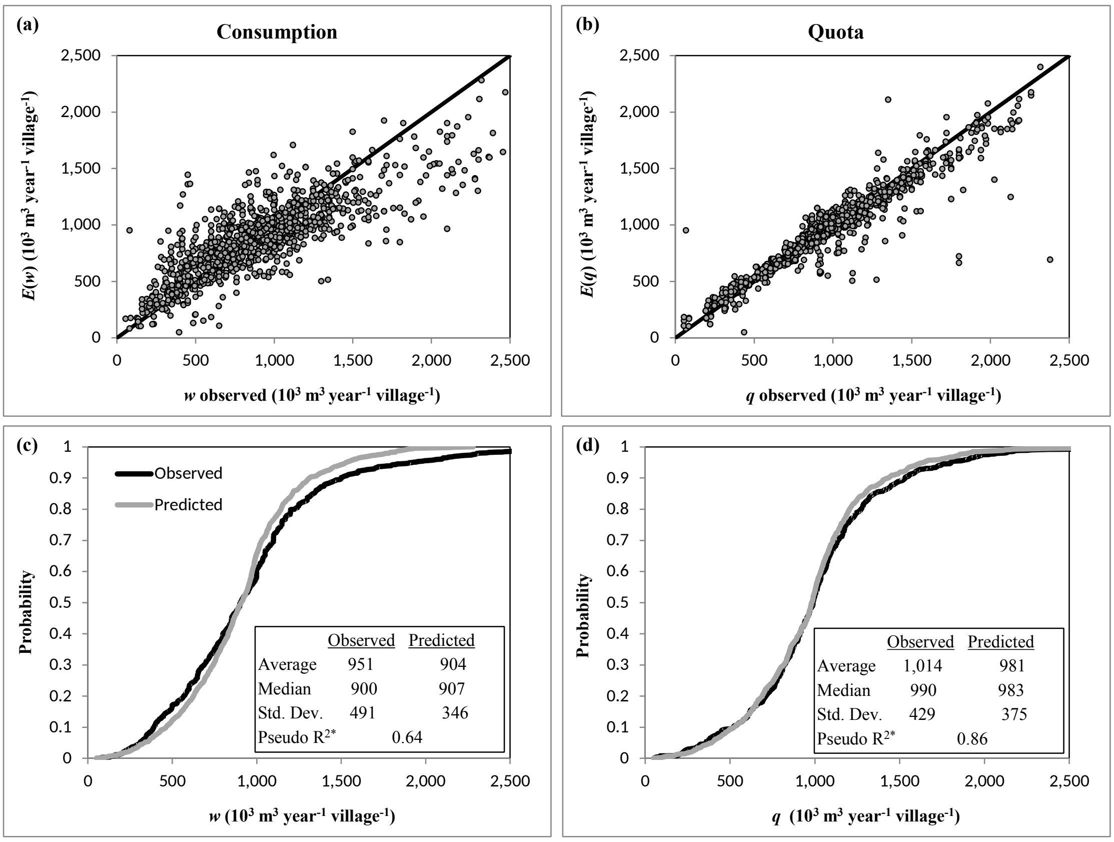

Figure 4 – Goodness-of-fit and moments of the distributions of the predicted and observed consumptions and quotas at the village level.

The estimated parameters of the quota-allocation function are consistent with the theory. The most notable result is the fact that the price coefficient is negative, statistically significant, and economically substantial. This result supports the theoretical finding that supplementing quantity instruments with prices reduces the intensity of the political lobbying for the enlargement of quotas and thereby elevates the efficiency (recall Figures 1 and 2).

Table 3 – Coefficients of the equations of the water demand and the quota-allocation rule (Eqs. 10 and 12), which are estimated at the village level.[a]

Variable	Demand Equation	Quota Equation
Price	-3,165*** (1,005)	-989.6*** (273.2)
Energy cost	-	-122.4** (50.5)
Capital & operation cost	-	41.76 (46.80)
Natural enrichment	-	0.031 (0.032)
Historical quota	-	0.786 (0.019)
Elevation above sea level	-0.627*** (0.096)	-
October precipitation	-0.841 (1.091)	-
April precipitation	-1.866 (1.660)	-1.733*** (0.428)
Annual precipitation	-0.028 (0.225)	-0.006 (0.067)
Agricultural land	0.134*** (0.026)	0.013*** (0.003)
Perennials' area	0.510*** (0.063)	0.047*** (0.011)
Light soil	-58.93 (51.68)	-21.39* (12.60)
Medium soil	-2,460 (35,871)	119.6*** (26.9)
Terms of trade	56.05* (32.68)	19.49** (7.93)
Center	5.619 (58.59)	62.59** (25.40)
South	228.6 (153.2)	61.76* (34.92)
Cooperative	-79.19 (70.63)	23.31 (16.03)
Minorities	823.1 (22,785)	-140.4*** (33.4)
$\ln\left(\sigma_{\gamma}\right)$	5.82*** (0.064)	-

$\ln(\sigma_{\varepsilon})$ – Agricultural land	0.0016*** (0.0001)	-
$\ln(\sigma_{\varepsilon})$ – Constant	4.92*** (0.05)	-
$\ln(\sigma_{u})$	-	5.03*** (0.02)

a. Numbers in parentheses represent standard errors; *, ** and *** indicate, respectively, significance levels of 0.1, 0.05 and 0.01.

Regarding other parameters, we note that the two components of the water-delivery cost operate in opposite directions: on the one hand, a higher energy cost, which indicates an increase in the marginal cost, increases the VMP under the political equilibrium in Eq. (3) and therefore negatively affects the allotted quotas in the equilibrium. On the other hand, capital and operational costs exhibit a positive (insignificant) coefficient. We expect a positive coefficient because larger capital costs indicate larger installed capacities, which are negatively correlated with the marginal costs (recalling the Hazen–Williams equation, a larger pipe diameter implies lower friction, and therefore a lower loss of energy in water supply); therefore, villages connected to capital-intensive enterprises enjoy comparatively larger quotas. Following Bar-Shira Finkelshtain and Simhon (2006), we introduce the historical quota as an indicator of the village's production capacity, and obtain a statistically significant coefficient. Higher terms-of-trade increase the quotas—a finding that verifies the prediction of the comparative statics with respect to the auxiliary parameter v. The interpretation of most of the other parameters in the quota equation is straightforward. The only exceptional parameter is the seemingly unintuitive sign of the April precipitation coefficient: while the impact of spring rainfalls on the demand is not statistically significant, a rainy year may reduce the pressure that farmers exercise to obtain higher quotas, and hence the negative sign in the quota-allocation equation.

Using the price coefficients of the demand and quota equations, we estimate the political preference ratio $\frac{\alpha}{1+\alpha}$ at about 0.31 (¿$\frac{-989.6}{-3,165}$), with a 95% confidence interval of [0.07,0.55]. This estimated political influence is slightly lower than that reported by Zusman and Amiad (1977), who estimated $\frac{\alpha}{1+\alpha}$ in the range of 0.4–0.6 for the Israeli dairy sector based on data from the late 1960s. On the other hand, that ratio is considerably higher than estimations obtained in studies of the impact of lobbying on trade policies (Gawande and Magee 2012). Therefore, we find that the government is not benevolent, but that the weight attached by policymakers to the welfare of the general public ($\frac{1}{1+\alpha}=0.69$) is larger than the weight that they assign to the benefits of the interest groups.

Table 4 reports the estimated parameters of the equation of the price formation at the regional level (Eq. 17). The data includes 72 region-year observations, and we account for heteroscedasticity by using the number of villages as a weight assigned to each region (weighting did not markedly affect the results). As we have already noted, we use exogenous variables (e.g., weather conditions) as instruments for the term $\frac{W_{jt}}{N_{jt}^{p}}$. The results suggest that marginal changes in the regional water consumption W_{jt} have a negative effect on the price p_{jt}. Therefore, in accordance with the logic of the backward induction, exogenous changes that increase the VMP of irrigation water lead to increased water demand and equilibrium quotas, which in turn intensify the lobbying efforts in the political arena of the first-stage price negotiations and yield a reduced price. This effect is further strengthened by the government's increased tendency to accommodate the farmers' pressure to reduce the price—a tendency that stems from the increased VMP. In addition, higher energy costs increase the equilibrium prices, whereas capital and operational costs have the opposite effect; these effects concur with those that we estimated based on the quota-allocation equation (Table 3). A larger natural enrichment of the reservoirs may lead to reduced scarcity rents, and therefore to a decrease in the equilibrium price.

We estimate the lobbying participation rate ϕ at 0.16 with a 95% confidence interval of [0.41,-0.1], which indicates the existence of considerable free riding with respect to the regional price (in comparison with lobbying for the village-specific quotas). In fact, the null hypothesis of negligible lobbying for lower regional prices is rejected only at the 10% level of significance.

Table 4 – Estimated parameters of the equation of the price formation at the regional level (Eq. 17).

Variable	**Coefficient**[a]
$\frac{W_{jt}}{N_{jt}^{p}}$ (instrumented[b])	$-3.6\times10^{-6***}(4.2\times10^{-7})$
Energy cost	0.12^{***} (0.02)
Capital & operation costs	-0.14^{***} (0.02)
Natural enrichment	$-1.2\times10^{-5***}$ (8×10^{-7})
Constant	0.067^{***} (8×10^{-4})

a. Numbers in parentheses represent standard errors; *, ** and *** indicate, respectively, significance levels of 0.1, 0.05 and 0.01. b. The instruments for $\frac{W_{jt}}{N_{jt}^{p}}$ include the October precipitation, the April precipitation, the elevation above sea level, and the years' and regions' fixed effects.

5. Simulations

Using the estimated parameters of the model, we develop a simulation framework for scenario analyses. The presence of random effects implies that predicted values are to be expressed in terms of expectations. Therefore, we use a numerical integration of the estimated bivariate likelihood function (Eq. 15) to compute the expected values of the following equilibrium elements at the village level (see Appendix G): the water usage $E(w^{it})$ and water quota $E(q^{it})$ (which are those presented in Figures 4a and 4b, respectively), the probability of a village being bound by the price $E\left(Pr\left[D\left(p^{it}, z^{it}\right) \leq q^{it}\right]\right)$, the VMP conditional on the quota being binding $E\left(\pi_w^{it} \middle| D\left(p^{it}, z^{it}\right) > q^{it}\right)$, the VMP at the water-usage level $E\left(\pi_w^{it}\right)$, and the deadweight loss relative to the socially optimal water allocation $E\left(DWL^{it}\right)$. In addition, we compute these elements for simulated equilibria under the quotas-only and price-only regimes.

The section starts with a discussion of water demand elasticity; we then evaluate the impact of exogenous changes and compare the hybrid policy to its two single-control counterparts. Finally, we decompose the deadweight loss, simulated under the quotas-only and price-only regimes, into three parts; each part is attributed to the impact of a different factor: demand elasticity, cost heterogeneity and free-riding.

5.1 Demand-Price Elasticity

Prices are endogenous in our model; nevertheless, one may wonder how the price affects water consumption. We distinguish three concepts of elasticity. The first concept is the "calculated demand elasticity," which we compute by utilizing the regression coefficient and evaluate at the sample-mean water usage (Tables 2 and 3); this elasticity is -0.91 (=-7,913×0.11/958). The second concept is the "constrained market elasticity," which corresponds to a market experiment in which villages constrained by their quota do not respond to changes in the price and in which we assume that the quotas are unresponsive to price changes. We conduct the calculation by simulating the expected water consumption $E\left(w^{it}\right)$ for prices that are 5% above and below the observed levels while holding the observed quotas constant. The elasticity thus computed is -0.28, which is higher than the short-run demand elasticity of -0.13 estimated by Bar-Shira Finkelshtain and Simhon (2006) for the Israeli agricultural sector in the period 1992–1997, but lower than the elasticity of -0.89 estimated by Finkelshtain Kan and Rapaport-Rom (2020) for the years 1996–2008.

Regarding the third elasticity concept, which accounts for the political mechanism, recall that as prices change in the first stage of the political game they induce quota changes in the second stage. A simulation of the quota expectation $E\left(q^{it}\right)$ with a 5% price change yields an "elasticity" of -0.27 of the equilibrium-quota rule with respect to the price. Accordingly, the third concept is the "unconstrained market elasticity," reached by simulating $E\left(w^{it}\right)$ with a price change of 5%, but this time allowing the quotas to change based on $E\left(q^{it}\right)$. The computed elasticity is now -0.50—almost twice as large as the "constrained market elasticity."

Many countries employ quantitative controls for irrigation water. The above findings imply that, at least for the conditions in Israel during the 1980s, an assertive price policy could greatly enhance the effectiveness of the direct-control instruments.

5.2 Exogenous Changes

In this subsection, we investigate the impact of exogenous shocks on the equilibrium characteristics of the hybrid policy and quantify the comparative statics effects presented in Table 1 with respect to selected equilibrium elements; Table 5 reports the results in terms of elasticities, which we evaluate at the sample average values.

Table 5 – Simulated responses of equilibrium elements to changes in the terms of trade, α, ϕ, and energy costs (expressed in terms of sample-average elasticities).

Equilibrium element	Baseline level	Game stage	Terms of trade	α	ϕ	Energy costs
p^{he} ($ m^{-3})	0.275	I	-9.15	-1.16	-0.49	0.16
$E\left(Pr\left[w \le p^{he}\right]\right)$	0.24	I	-42.1	4.65	-1.55	0.52
$E\left(q^{he}\right)$ (10^3 m^3 year^{-1} village^{-1})	981	II	3.65	0.13	0.13	-0.04
$E\left(w\right)$ (10^3 m^3 year^{-1} village^{-1})	951	II	4.05	0.18	0.15	-0.05

We start with the baseline-simulated conditions, which Table 5 portrays in its second column. The equilibrium price p^{he} is the predicted average value of Eq. (17), and the expected consumption and quota are the sample-average of the simulated values, which Figure 4c and 4d report, respectively. The average expected probability that the price acts as the binding factor $E\left(Pr\left[w \le p^{he}\right]\right)$ is 0.24, which appears to be half of the above-mentioned "naive" observation that consumption is lower than the quota in 48% of the sample (recall Figure 3a); this finding demonstrates the importance of accounting for the distributions of the random variables γ and ε.

Considering the exogenous changes, the third column in Table 5 indicates the stage of the political game through which the equilibrium characteristics are set, and columns 4–7 show the effects of changes in four exogenous factors: terms of trade, α, ϕ, and energy costs. The first two rows of Table 5 show variations in the elements associated with the first stage: p^{he} and $E\left(Pr\left[w \le p^{he}\right]\right)$. We calculate the change in the price using Eq. (17); in this equation, W_{jt} equals the regional sum of the expected consumption at the village level $E\left(w^{it}\right)$ and $N_{jt}^{p} = N_j E\left(Pr_j\left[D\left(p^{it}, z^{it}\right) \le q^{it}\right]\right)$, in which N_j is the number of villages in region j and $E\left(Pr_j\left[D\left(p^{it}, z^{it}\right) \le q^{it}\right]\right)$ is region-j's average expected probability of the quota being non-binding. The last two rows present the second-stage effect, which we compute by introducing the exogenous change and the updated price from the first stage into the equations of the equilibrium elements (Appendix G) while allowing the quotas to change according to the estimated function $Q\left(p^{it}, x^{it}, z^{it}\right)$.

The comparative statics analyses (Table 1) predict that improvement in the terms of trade leads to a reduced price and to increased quotas and water usage. The results of the simulation (column 4 in Table 5) demonstrate that these effects are sizeable. Note, in particular, that the elasticity of the water price with respect to the terms of trade is -9.15. In the last seven decades, since the establishment of the state of Israel (1948), the terms of trade of crops in Israel have declined by more than 60% while water prices have increased by a factor of six. Political scientists (e.g., Menahem 1998) tend to attribute these changes to erosion in the intensity of lobbying by farmers and/or in the attitudes of society and politicians towards agriculture. Our political-economic model, in which the levels of the political organization (ϕ) and governmental norms (α) are steady, provides an alternative explanation to the increase in the water price; namely, an exogenous decline in the terms of trade.

The elasticities of the equilibrium water-usage and quota, with respect to both α and ϕ, are less than 1. However, those elasticities are substantial, and tend to be similar in their magnitudes. While lower costs of communication may lead to an increased transparency of governmental policies and to higher ethical norms (i.e., lower α), they may also strengthen the political organization and lobbying of farmers (i.e., larger ϕ) (Anderson 1995); the results of the simulations suggest that such changes may offset each other, and thereby perpetuate the overutilization of water resources.

5.3 Comparing the Hybrid Regime with its Quotas-Only and Price-Only Counterparts

Compared to a quotas-only policy, the hybrid control leads to larger VMPs and to smaller water utilization across the board; however, the VMPs of a subset of the price-bound users exceed their marginal costs (Figure 3). A price-only regime is, by definition, a second-best solution because of the presence of heterogeneous marginal supply costs, but, because of free-riding, it attracts less political pressure than a hybrid control does. Therefore, as we have noted above, a normative ranking of the hybrid, quotas-only, and price-only regimes is an empirical question.

In addition to studying the normative ranking of the three policies, we study the factors that underlie the societal rank of the price and quotas as exclusive regulations. FK showed that, under homogenous costs, if the demand elasticity is higher than the share of the resource utilized by the politically organized users, then, in terms of efficiency, a price-only policy dominates a quotas-only regime. Considering the estimated parameters in our study (a demand elasticity of -0.91 and a lobbying participation rate of 0.16), one would expect a dominance of the price regime. However, here we extend FK's framework by incorporating heterogeneous water-supply costs and thereby introduce an additional source of welfare-loss with respect to a uniform price. We therefore decompose the impact of the three factors on the relative efficiency of the price-only and quotas-only regimes under lobbying: demand elasticity, free-riding, and cost heterogeneity. To that end, we separate the price-only regulation into two pricing schemes: a regionally uniform price and village-specific prices (see Appendix G); a comparison of these two scenarios enables us to assess the welfare effect of the intra-regional variability of the marginal costs. To quantify the effect of free-riding, we simulate the price regime in the extreme case of perfect lobbying ($\phi = 1$) under both the regionally uniform and the village-specific price settings.

Table 6 reports the results in terms of sample averages. The columns marked I, II, and III present the results under the hybrid, quotas-only and price-only (the scenario in which the price is uniform and $\phi = 0.16$) regimes, respectively. As the theory predicts, the expected VMP under the simulated hybrid regime exceeds that of the quotas-only regime (0.45 \$ m^{-3} versus 0.38 \$ m^{-3}), and therefore the per-village annual water usage under the hybrid regime is relatively lower (951,000 m^3 versus 1,230,000 m^3). From a welfare perspective, the hybrid regime is clearly favorable to the quotas-only regime: the per-village annual deadweight loss is \$45,000 under the former compared to \$65,800 under the latter. Evidently, the price-only regime fares worse in terms of welfare—its deadweight loss is about 110% as large as that of the hybrid policy. Given that, under the price-only regime, the VMP is the largest (0.52 \$ m^{-3}) and the water usage is the lowest (915,000 m^3 year^{-1} village^{-1}), we attribute the inferiority of that policy to the presence of a large heterogeneity in marginal water-supply costs. Indeed, the scenarios of price-only regimes with village specific prices and a uniform price yield the same expected VMP (0.52 \$ m^{-3}), but the deadweight loss in the scenario of the village specific prices is considerably lower (800 m^3 year^{-1} village^{-1}).

Table 6 – Equilibrium elements simulated under the hybrid, quotas-only, and price-only regimes (evaluated at the sample average).

			Price-only regimes			
			Uniform price		**Village-specific price**	
	Hybrid regime	**Quotas-only regime**	$\phi = 0.16$	$\phi = 1$	$\phi = 0.16$	$\phi = 1$
Equilibrium element	I	II	III	IV	V	VI
$E\left(\pi_w\left(w\right)\right)$ (\$ m^{-3})	0.45	0.38	0.52	0.37	0.52	0.37
$E\left(w\right)$ (10^3 m^3 year^{-1} village^{-1})	951	1,230	915	1,391	850	1,439
$E\left(DWL\right)$ (10^3 \$ year^{-1} village^{-1})	45.0	65.8	96.3	158.8	0.8	83.8

We now consider the expectations of deadweight losses that are simulated under the single-control regimes (column II versus III); expectations that reflect the superiority of the quotas-only policy in relation to the price-only alternative. We decompose the difference in the deadweight losses between these two policies to the effects of the demand elasticity, cost heterogeneity, and free-riding. The effect of the demand elasticity can be evaluated by the difference in the deadweight losses between the quotas-only regime (column II) and the hypothetical village-specific price-only policy under perfect political organization (column VI); this difference amounts to \$18,000 (= \$83,800 minus \$65,900). We elicit the effect of the marginal cost heterogeneity based on the four price-only simulations (columns III to VI) by comparing the uniform-price to the village-specific-prices scenarios; this effect amounts to \$95,500 (= \$96,300 minus \$800) under $\phi = 0.16$ (columns III minus V) and \$75,000 (= \$158,800 minus \$83,800) under $\phi = 1$ (column IV minus VI). Likewise, we use the price-only regimes for an evaluation of the free-riding effect, and receive results of \$62,500 (= \$158,800 minus \$96,300) and \$83,000 (= \$83,800 minus \$800) under the regionally uniform and village-specific prices, respectively. Therefore, the dominance of the quotas-only policy over the price-only policy stems from the fact that the sum of the welfare impacts of the demand-elasticity and the marginal cost variability (\$80,500 to \$101,000) is larger than that of the free-riding (\$75,000 to \$95,500).

7. Summary and Limitations

Realizing that political involvement tends to distort resource-allocation and reduce social welfare, in 2007 the Israeli Parliament amended the water law and established an independent Water Authority with the power to determine water allotments and prices. The new law specifically and explicitly prevented the minister responsible for the water sector from intervening in the Water Authority's areas of responsibility. While the parliament's intent was laudable, eventually the legislators could not adhere to the law that they had enacted, and could not resist the temptation to influence prices. The legislators therefore threatened that if price structuring had not become consistent with political desires, they would have amended the law—a threat that reflected the public outcry and the goals of interest groups. It seems impossible to curb the administrative functions from interfering in the political process. Given this axiom, this paper suggests that a hybrid policy that combines quantity controls with market-based instruments can increase a regulation's robustness to political distortions.

Our empirical analysis may fail to capture various factors that affected the irrigation-water policies in Israel, and therefore the estimated distortion attributed to political pressures is potentially biased. For example, if, while setting water prices and quotas, policymakers considered the positive external effects of irrigation water (e.g., open-space services provided by vegetative agriculture; see Fleischer and Tsur 2000), then our estimated parameter α would have incorporated these effects; in this case, we would have overvalued the political power assigned to the agricultural sector. However, Kan et al. (2009) showed that internalizing the benefits of a rural landscape into the considerations of farmers in Israel is expected to hardly alter the patterns of agricultural production. Another possible argument is that regulators might have accounted for the support provided by local agriculture to the food independence of Israel as a geopolitically isolated country (Morag 2001). Nevertheless, Israel's import of virtual water in the form of grains is nearly three times larger than the total annual irrigation-water consumption—a fact that implies that food independence is unattainable under the prevailing patterns of food consumption (Kislev 2001). On the other hand, an undervaluation of α may emerge in the presence of external benefits of alternative freshwater usages, such as discharge into natural waterways to provide recreation and ecosystem services. However, environmental benefits seem to have been a minor consideration in Israel's policymaking during the 1980s; water was officially allotted to nature only in 2013 (Israel Ministry of Environmental Protection 2013), and even then the regulated allocation (50 million m^3 per year) constituted less than 3% of the total annual water supply.

Regarding the level of regional political organization, the estimated parameter ϕ measures the degree of political participation in relation to the involvement of the quota-bound villages in lobbying for the enlargement of their private quotas. However, the participation in the quota game is unidentifiable, and if it is incomplete (e.g., because of lobbying transaction costs), then ϕ is underestimated, whereas α is overestimated. In addition, ϕ may reflect other policy considerations with respect to quotas versus prices, such as differences in bureaucracy and transparency.

We conclude by mentioning potential avenues for future research. The theoretical findings of this paper indicate that, while it enhances the robustness of prices and quotas to political distortion, the hybrid policy may be ranked lower than the exclusive-instrument regimes in terms of welfare. Therefore, the optimal policy may vary across regions and across periods. Applying the model to other water economies that integrate quantitative and price controls may necessitate adjustments in relation to the local institutional and economic conditions. For example, while the decision making with respect to price and quotas in Israel is sequential, in other places regulations may be applied simultaneously; our framework could account for this regulation-setup with some modeling modifications.

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Appendix A – Proof of Proposition 1

According to condition (b) of Proposition 1 of GH, the vector of the equilibrium quotas maximizes the government's objective G. We assume a local differentiability of r_i^q, and, in relation to Eq. (2), obtain that the necessary condition for this maximization is:

$$\alpha \sum_{i=1}^{N} \nabla r_i^q + \nabla S\left(q^{he}\right) = 0. \qquad \text{(A1)}$$

However, condition (c) of Proposition 1 of GH implies that $\nabla r_i^q = \nabla y^i \forall i \in N$; we substitute this equality into Eq. (A1), and, given that farms with binding quotas are characterized by $S_{q^i} = \pi_w^i - c_{w^i}$, $y_{q^i}^i = \pi_w^i - p$ and $y_{q^l}^i = 0 \forall l \neq i$, we get Eq. (3).

Appendix B – Globally Truthful Contribution Schedules and Equilibrium Uniqueness

Under globally truthful contribution schedules, the contributions satisfy $r_i^q = y^i - r_i^p - B_i \forall i \in N$, in which r_i^p (i.e., farm-i's contribution to the regional lobby) is known from the first-stage price game, and B_i is a positive constant to be determined by the equilibrium. Define

$$q^{-j} \equiv \underset{q}{argmax} \left\{ \alpha \sum_{i \in Q \text{¿}} \left(y^i \left(q^i \right) - r_i^p - B_i \right) + S\left(q\right) \right\} \forall i \in Q \quad \text{(B1)}$$

as the choice of quotas when farm j refrains from lobbying. According to Proposition (1) of GH, the set of equilibrium constants B_i^{he}, $i \in Q$, satisfies the following system of equations:

$$\alpha \sum_{i \in Q} \left(y^i \left(q_i^{he} \right) - r_i^p - B_i^{he} \right) + S\left(q^{he} \right) = \text{¿}\, \alpha \sum_{i \in Q \text{¿}} \left(y^i \left(q_i^{-j} \right) - r_i^p - B_i^{he} \right) + S\left(q^{-j} \right) \forall i \in Q, \quad \text{(B2)}$$

in which q_i^{-j} is the i element of the vector q^{-j}.

Note that this equilibrium condition does not determine the contribution r_i^p for all $i \in L$ (i.e., the allocation of the contribution of the regional lobby r^p among the L contributing farms). To ensure the uniqueness of the equilibrium, we assume that the lobbying costs are shared by some rule that is known to all agents in the economy, but is not formulated explicitly here. Under this condition, a monotonicity of $S(\cdot)$ and $y^i(\cdot)$ assures a unique solution to the system in Eq. (B2).

Appendix C – Proof of Proposition 2

Once more, we employ Proposition 1 of GH and assume a local differentiability of the contribution schedule of the regional lobby. A maximization of G in Eq. (2) implies that:

$$\begin{gathered}\alpha\frac{\partial r^p}{\partial p}+\sum_{i\notin Q}\left(\pi_w^i-c_{w^i}\right)D_p^i+\sum_{i=1}^{N}\left[\alpha\frac{\partial r_i^q}{\partial q^i}+\left(\pi_w^i-c_{w^i}\right)\right]\frac{\partial q_i^{he}}{\partial p}=0\\ \Longleftrightarrow\alpha\frac{\partial r^p}{\partial p}+\sum_{i\notin Q}\left(\pi_w^i-c_{w^i}\right)D_p^i=0,\end{gathered}\tag{C1}$$

in which the equivalency follows from the maximization of G in the second stage; a maximization that implies that the expression in the square brackets vanishes (according to the envelope theorem). By maximizing the joint welfare of the government and farms' lobby $Y+G$ and using Eq. (C1), we obtain:

$$\sum_{i\in L}w^i-\frac{\partial r^p}{\partial p}+\sum_{i=1}^{N}\left(\pi_w^i-p^{he}-\frac{\partial r_i^q}{\partial q^i}\right)\frac{\partial q_i^{he}}{\partial p}+\alpha\frac{\partial r^p}{\partial p}+\sum_{i\notin Q}\left(\pi_w^i-c_{w^i}\right)D_p^i=0\tag{C2}$$

However, it follows from the second-stage equilibrium that $\pi_w^i-p^{he}=\frac{\partial r_i^q}{\partial q^i}\ \forall i\in Q$, and that for all $i\notin Q$ $\pi_w^i-p^{he}=0$ and $\frac{\partial r_i^q}{\partial q^i}=0$; these equalities imply that $\left(\pi_w^i-p^{he}-\frac{\partial r_i^q}{\partial q^i}\right)\frac{\partial q_i^{he}}{\partial p}=0$. Moreover, according to Eq. (C1), $\alpha\frac{\partial r^p}{\partial p}+\sum_{i\notin Q}\left(\pi_w^i-c_{w^i}\right)D_p^i=0$. Taken together, these last two equalities can be used to rewrite Eq. (C2) as $\sum_{i\in L}w^i=\frac{\partial r^p}{\partial p}$. We substitute the last equality into Eq. (C1) and use the identities $\sum_{i\in L}w^i=\phi\sum_{i\in N}w^i=\phi\left[\sum_{i\in Q}q_i^{he}\left(p^{he}\right)+\sum_{i\notin Q}D^i\left(p^{he}\right)\right]$ to get Eq. (7).

A formal proof of the existence and uniqueness of a perfect Nash equilibrium in the two-stage price-quota game is beyond the scope of this paper. Instead, we provide an informal discussion of the matter. First, we assume that $\pi^i(w^i)$ and the farm's net income are concave and differentiable (the net income constitutes the farm's objective function in the second-stage quota game). Considering our additional assumption that $c(w)$ is convexly increasing and differentiable, the second-stage objective function of the government $G(q)$ is also concave and differentiable. Thus, all of the conditions underlying Proposition1 of GH are fulfilled—a fact that ensures the existence of a perfect Nash equilibrium in the second-stage game. In accordance with GH's framework, uniqueness is ensured under the truthfulness refinement. All that remains is to justify the existence and uniqueness of the first-stage price game. Because the first-stage objective functions of the government and the farms are concave and differentiable with respect to q^{he} and r_i^q, the uniqueness and existence of the equilibrium, based on Proposition 1 of GH, is assured.

Appendix D – Existence of a Separating Equilibrium

Proposition: *If* $p^{he}=\{\underline{p}^{he},\dots,\overline{p}^{he}\}$ *is the set of possible separating-equilibrium prices in a hybrid regime, a sufficient condition for the existence of* $p^{he}\in p^{he}$ *is that, under* p^{he}*, there exist:*

(a) at least one farm $i\in N$ *for which the historical quota is large enough to satisfy*

$$\breve{q}_i>\pi_w^{i\;-1}\left(\sum_{i\in I}c_{w^i}\frac{s^i|\eta^i|}{\sum_{i\in I}\left(s^i|\eta^i|\right)+\alpha\phi}\right)$$

, in which I *is the group of price-bound farms under the lowest-possible separating-equilibrium price* $\underline{p}^{he}$*;*

(b) at least one farm $i\in N$ *for which the historical quota* $\breve{q}_i$ *is small enough to satisfy*

$$\breve{q}_i<\pi_w^{i\;-1}\left(\sum_{i\in N}c_{w^i}\frac{s^i|\eta^i|}{\sum_{i\in N}\left(s^i|\eta^i|\right)+\alpha\phi}\right).$$

D.1 Condition (a)

Condition (a) excludes the case of a pooling-quotas equilibrium (i.e., $Q=N$). We first describe a situation under which the pooling-quotas equilibrium is guaranteed, and then formulate the condition that excludes such an equilibrium.

According to Eq. (3), the equilibrium-quota rule implies that $c_{w^i}>\pi_w^i\left(q_i^{he}\right)>p$ prevails for any price p, as long as $\alpha>0$. Suppose that the historical quotas are set so that $max\left(\breve{q}_i,q_i^{he}(p)\right)=q_i^{he}(p)$ for all $i\in N$ (for example, this prevails in case the allocation of historical quotas corresponds the socially optimal allocation: $\breve{q}_i=q_i^o=\pi_w^{i^{-1}}\left(c_{w^i}\right)$ for all $i\in N$). This situation implies that if a separating-equilibrium price p^{he} exists, then the quota-bound group is dictated only by the equilibrium-quota rule $q_i^{he}\left(p^{he}\right)$: $Q\equiv\left\{i\in N: q_i^{he}\left(p^{he}\right)\leq D_i\left(p^{he}\right)\right\}$. Therefore, according to Eq. (3), some farm $n\in Q$, whose marginal cost is $c_{w^n}\geq\underline{c}_w$, exists, and its quota q_n^{he} satisfies the identities:

$$p^{he}=\pi_w^n\left(q_n^{he}\right)=\frac{c_{w^n}+\alpha p^{he}}{1+\alpha}\Longleftrightarrow$$

$$p^{he}=c_{w^n}; \tag{D1}$$

the quota q_i^{he} of any other quota-bound farm i satisfies $\pi_w^i\left(q_i^{he}\right)\geq p^{he}$; this fact implies that $c_{w^i}\geq c_{w^n}$ for all $i\in Q$, $i\neq n$. In other words, under that hybrid separating-equilibrium, c_{w^n} is the lowest marginal cost among the quota-bound farms, whereas the marginal costs of all price-bound farms fall short of c_{w^n}. However, according to Eq. (8) and for the case of $\alpha\phi>0$, the equilibrium price p^{he} is lower than the weighted average of the marginal costs of the price-bound farms—a fact that implies that

$$p^{he}=\sum_{i\notin Q}c_{w^i}\frac{s^i\left|\eta^i\right|}{\sum_{i\notin Q}\left(s^i\left|\eta^i\right|\right)+\alpha\phi}<c_{w^n}. \tag{D2}$$

This inequality contradicts Eq. (D1).

Therefore, if $\breve{q}_i<q_i^{he}\left(p\right)$ for all $i\in N$, then a separating political equilibrium cannot emerge even in the case of $c_{w^n}=\underline{c}_w$. In this case the price is zeroed, and the pooling-quotas equilibrium emerges so that $\pi_w^i\left(q_i^{he}\right)=\frac{c_{w^i}}{1+\alpha}$ for all $i\in N$. This outcome implies that, if a separating equilibrium price p^{he} exists, then the price must involve at least one farm $i\in N$ for which $\breve{q}_i>q_i^{he}\left(p^{he}\right)$. Condition (a) defines the minimal level of $\breve{q}_i$ that is required to exclude the case of the pooling-quotas equilibrium.

As we have defined above, l is the subgroup of price-bound farms under the minimal separating-equilibrium price p^{he} so that

$$\underline{p}^{he}=\sum_{i\in l} c_{w^i}\frac{s^i|\eta^i|}{\sum_{i\in l}\left(s^i|\eta^i|\right)+\alpha\phi}. \tag{D3}$$

For l to be a non-empty group, at least one farm $i\in N$ for which $\breve{q}_i>{\pi_w^i}^{-1}\left(\sum_{i\in l} c_{w^i}\frac{s^i|\eta^i|}{\sum_{i\in l}\left(s^i|\eta^i|\right)+\alpha\phi}\right)$ should exist; this fact verifies Condition (a).

Notice that, because $\underline{p}^{he}$ is incorporated in the terms $s^i|\eta^i|$ on the R.H.S of Eq. (D3), $\underline{p}^{he}$ is an implicit function. To illustrate a simpler case, let us suppose that all of the region's farms share the same VMP function $\pi^i(w^i)=\exp\left(\frac{A-w^i}{B}\right)$; this supposition implies that $w^i|\eta^i|=B$ for all $i\in N$ so that $s^i|\eta^i|=s|\eta|$ for all of the farms (recall the following identities: $D_i(p)=A-B\ln(p)\Longrightarrow\eta=\frac{dw^i}{dp}\frac{p}{w^i}=\frac{-B}{w^i}\Longrightarrow w^i|\eta|=B$). Let farm l be the single farm whose marginal cost c_{w^l} is the lowest in the region: $c_{w^l}=\underline{c}_w$. Under these specifications, the lowest possible separating-equilibrium price is

$$\underline{p}^{he}=\frac{s|\eta|c_{w^l}}{s|\eta|+\alpha\phi}, \tag{D4}$$

in which the set of price-bound farms l includes only farm l. However, for farm l to be included in l, farm-l's historical quota must satisfy $\breve{q}_l>{\pi_w^l}^{-1}\left(\frac{s|\eta|c_{w^l}}{s|\eta|+\alpha\phi}\right)$. Note that any other farm $i\neq l$ (whose marginal cost $c_{w^i}>c_{w^l}$) for which $\breve{q}_i>{\pi_w^l}^{-1}\left(\frac{s|\eta|c_{w^l}}{s|\eta|+\alpha\phi}\right)$ would be a price-bound farm under $\underline{p}^{he}$, and also under any price larger than $\underline{p}^{he}$; therefore, a sufficient condition for the exclusion of a pooling-quotas equilibrium is the presence of at least one farm $i \in N$ for which $\breve{q}_i > \pi_w^{l\ -1}\left(\frac{s|\eta| c_{w^l}}{s|\eta| + \alpha\phi}\right)$.

D.2 Condition (b)

Condition (b) excludes the emergence of a polling-price equilibrium; we prove the condition by contradiction. Assume the existence of a set of historical quotas $\breve{q}$ and of a separating hybrid-equilibrium price $p^{he} \in p^{he}$ under which $\breve{q}_i > q_i^{he}\left(p^{he}\right)$ for all $i \in N$. In this case, $Q \equiv \left\{ i \in N : \breve{q}_i \leq D_i\left(p^{he}\right) \right\}$; in other words, only the vector $\breve{q}$ determines the set Q under p^{he}, and $\pi_w^i\left(q_i^{he}\right) > \pi_w^i\left(\breve{q}_i\right)$ for all $i \in N$. Additionally, let $\breve{q}_k$ be the historical quota of farm k whose VMP $\pi_w^k\left(\breve{q}_k\right)$ (i.e., evaluated at $\breve{q}_k$) is the largest among all N farms.

Consider the political-equilibrium price under a price-only regime:

$p^{pe} = \sum_{i \in N} c_{w^i} \frac{s^i|\eta^i|}{\sum_{i \in N}\left(s^i|\eta^i|\right) + \alpha\phi}$. If $\breve{q}_k$ is large enough so that $p^{pe} > \pi_w^k\left(\breve{q}_k\right)$, then $D_i\left(p^{he}\right) < \breve{q}_i$ for all $i \in N$; this fact implies that all farms in the region are bound by the price (i.e., $Q \neq \varnothing$) so that $p^{he} = p^{pe}$. However, this situation contradicts our assumption that the price p^{he} is a separating-equilibrium price. Therefore, a separating equilibrium requires at least one farm $i \in N$ for which the historical quota is small enough to satisfy $\pi_w^i(\breve{q}_i) > p^{pe}$; as stated by Condition (b): $\breve{q}_i < \pi_w^{i\ -1}\left(\sum_{i \in N} c_{w^i} \frac{s^i|\eta^i|}{\sum_{i \in N}\left(s^i|\eta^i|\right) + \alpha\phi}\right)$.

<u>D.3 The Equilibrium in the Case that the Historical Quotas of the Hybrid-Policy are Determined under a Quotas-Only Regime</u>

Suppose that a quotas-only regime is replaced by a hybrid regime, in which the historical quotas are determined under the hitherto quotas-only regime. In this case, for any price p under the hybrid policy the inequality $\frac{c_{w^i}}{1+\alpha} < \frac{c_{w^i} + \alpha p}{1+\alpha}$ prevails for all $i \in N$; therefore, $\breve{q}_i > q_i^{he}(p)$ for all $i \in N$. Consequently, under a given separating-equilibrium price p^{he}, only the historical quotas $\breve{q}$ determine the set of quota-bound farms Q. Assume again that $s^i|\eta^i| = s|\eta|$ for all farms, and that only one farm $l \in N$, whose marginal cost c_{w^l} is the lowest ($c_{w^l} = \underline{c}_w$), and only one farm $k \in N$, whose marginal cost c_{w^k} is the highest ($c_{w^k} = \bar{c}_w$), exist. Then, because the VMP under the quotas-only regime $\frac{c_{w^l}}{1+\alpha}$ determines the largest historical quota of farm l, Condition (a) becomes

$$\frac{s|\eta| c_{w^l}}{s|\eta| + \alpha\phi} > \frac{c_{w^l}}{1+\alpha} \Longleftrightarrow$$

$$s|\eta| > \phi. \qquad \text{(D5)}$$

The VMP $\frac{c_{w^k}}{1+\alpha}$ determines the lowest historical quota of farm k under the quotas-only regime, and therefore Condition (b) becomes

$$\frac{c_{w^k}}{1+\alpha} > \sum_{i\in N} c_{w^i} \frac{s|\eta|}{\sum_{i\in N} (s|\eta|) + \alpha\phi}. \tag{D6}$$

Note that if the marginal costs are identical for all farms, then Eqs. (D5) and (D6) form together the condition

$$\frac{s|\eta|}{s|\eta| + \alpha\phi} > \frac{1}{1+\alpha} > \frac{\sum_{i\in N} s|\eta|}{\sum_{i\in N} (s|\eta|) + \alpha\phi}, \tag{D7}$$

which cannot be met. Therefore, if the marginal costs do not differ much across farms, it is likely that either a pooling-price equilibrium or a pooling-quotas equilibrium will emerge.

Appendix E – Comparative Statics

The recursive decision-making process implies that the comparative statics analyses should follow a two-stage procedure. We first examine the effect of a change in an exogenous parameter on the price. Then, we analyze the direct impact of the change in the exogenous parameter on the quotas together with the indirect effect that is channeled through the price (considering the discrete distribution of villages, we assume that marginal changes in the price and quotas do not alter the price- and quotas-bound groups).

E.1 The Impact on the Price

In view of Eq. (7), $\frac{d p^{he}}{d\tau} = \frac{-G_{p\tau}}{G_{pp}}$ for any exogenous parameter τ; because $G_{pp} < 0$, the sign of $\frac{d p^{he}}{d\tau}$ is equal to that of $G_{p\tau}$. The results with respect to α, ϕ, c_{w^i}, and v are:

$$G_{p^{he}\alpha} = -\phi \sum_{i\in Q} q_i^{he}\left(p^{he}\right) + \sum_{i\notin Q} D^i\left(p^{he}\right) < 0; \tag{E1}$$

$$G_{p^{he}\phi} = -\alpha \sum_{i\in Q} q_i^{he}\left(p^{he}\right) + \sum_{i\notin Q} D^i\left(p^{he}\right) < 0; \tag{E2}$$

$$G_{p^{he}c_{w^i}} = -D^i_p\left(p^{he}\right) > 0; \tag{E3}$$

$$G_{p^{he}v} = \sum_{i \notin Q} \pi^i_{wv} D^i_p - \alpha \sum_{i \in L} D^i_v\left(p^{he}\right) < 0, \tag{E4}$$

(we assume that $D^i_{pv} = 0$).

E.2 The Impacts on the Quotas

We hold the equilibrium price p^{he} from the first constant. According to Eq. (3), the direct effect of any exogenous parameter τ on the equilibrium quota is given by

$\frac{d\,q_i^{he}}{d\tau} = \frac{-G_{q^i\tau}}{G_{q^iq^i}}$; because $G_{q^iq^i} < 0$, the sign of $\frac{d\,q_i^{he}}{d\tau}$ is determined by that of $G_{q^i\tau}$. The results regarding α, ϕ, c_{w^i}, and v are:

$$G_{q_i^{he}\alpha} = \pi^i_w\left(q_i^{he}\right) - p^{he} > 0 \ \forall\, i \in Q; \tag{E5}$$

$$G_{q_i^{he}\phi} = 0 \ \forall\, i \in Q; \tag{E6}$$

$$G_{q_i^{he}c_{w^i}} = \frac{-1}{\alpha} < 0 \ \forall\, i \in Q; \tag{E7}$$

$$G_{q_i^{he}v} = \left(1 + \alpha\right)\pi^i_{wv} > 0 \ \forall\, i \in Q. \tag{E8}$$

Because $\frac{d\,q_i^{he}}{d\,p^{he}} < 0 \ \forall\, i \in Q$, the signs of the direct impacts of the marginal changes in the parameters α, c_{w^i}, and v on the equilibrium quota coincide with the signs of the indirect impacts that these changes impose on the equilibrium quota through the equilibrium price (Eqs. E1, E3 and E4, respectively). Regarding the parameter ϕ, the indirect effect (Eq. E2) implies that $\frac{d\,q_i^{he}}{d\phi} > 0$ because the direct effect vanishes.

Appendix F – Specification of the Probability Function

Let $g_\gamma(\gamma)$, $g_\varepsilon(\varepsilon)$ and $g_u(u)$ be the probability density function (PDF) of γ, ε and u, respectively; we assume that these PDFs are independent. Define $\varphi \equiv \gamma + \varepsilon$, and let $g_{\varphi\gamma}(\varphi, \gamma)$ denote the joint PDF of φ and γ. We specify $g_{\varphi\gamma}(\varphi, \gamma)$ as the bivariate normal PDF, which includes the parameters σ_γ^2, $\sigma_\varphi^2 = \sigma_\gamma^2 + \sigma_\varepsilon^2$ and

$\rho = \dfrac{Cov(\gamma, \gamma + \varepsilon)}{\sigma_\varphi \sigma_\gamma} = \dfrac{\sigma_\gamma^2}{\sqrt{(\sigma_\gamma^2 + \sigma_\varepsilon^2)\sigma_\gamma^2}} = \dfrac{\sigma_\gamma}{\sigma_\varphi}$. In the same manner, $g_{\varphi\gamma u}(\varphi, \gamma, u)$ and $g_{\gamma\varepsilon u}(\gamma, \varepsilon, u)$ are the joint PDFs of φ, γ and u, and of ε, γ and u, respectively. The PDF of γ conditional on φ (denoted $g_{\gamma|\varphi}(\gamma|\varphi)$) implies that $g_{\varphi\gamma}(\varphi, \gamma) = g_{\gamma|\varphi}(\gamma|\varphi) g_\varphi(\varphi)$. Because of the independence of γ, ε and u, one obtains that $g_{\varphi\gamma u}(\varphi, \gamma, u) = g_{\gamma|\varphi}(\gamma|\varphi) g_\varphi(\varphi) g_\varepsilon(\varepsilon)$ and that $g_{\gamma\varepsilon u}(\gamma, \varepsilon, u) = g_\gamma(\gamma) g_\varepsilon(\varepsilon) g_u(u)$. We omit the unessential indices and function operators, and express, in terms of the PDFs, the probability of observing a certain pair of w and q^t as:

$$Pr(w, q^t, \theta) = ¿\, g_\varphi(w - D) g_u(q^t - q^{t-1}) \int_{-\infty}^{\hat{\gamma}} g_{\gamma|\varphi}(\gamma|\varphi) d\gamma + g_\varepsilon(w - q^t) g_u(q^t - D) \int_{\hat{\gamma}}^{\infty} g_\gamma(\gamma) d\gamma, \qquad \text{(F1)}$$

in which $\hat{\gamma} = q^t - D$. Because $g_{\varphi\gamma}(\varphi, \gamma)$ is the a bivariate normal PDF, the distribution of $g_{\gamma|\varphi}(\gamma|\varphi)$ is $N(\rho^2 \varphi, \sigma_\gamma^2(1 - \rho^2))$. We use f and F to denote the density and cumulative-density functions of a standard normal random variable, respectively, to obtain the probability function:

$$Pr(w, q^t, \theta) = ¿\, \frac{1}{\sigma_\varphi} f\left(\frac{w - D}{\sigma_\varphi}\right) \frac{1}{\sigma_u} f\left(\frac{q^t - q^{t-1}}{\sigma_u}\right) F\left(\frac{\hat{\gamma} - \rho^2(w - D)}{\sigma_\gamma \sqrt{(1 - \rho^2)}}\right) + \frac{1}{\sigma_\varepsilon} f\left(\frac{w - q^t}{\sigma_\varepsilon}\right) \frac{1}{\sigma_u} f\left(\frac{q^t - Q}{\sigma_u}\right) F\left(\frac{-\hat{\gamma}}{\sigma_\gamma}\right). \qquad \text{(F2)}$$

Appendix G – Simulated Expected Values

G.1 The Hybrid Equilibrium

In accordance with the bivariate likelihood function (Eq. 15), the expected village-level water usage $E\left(w^{it}\right)$ and quota $E\left(q^{it}\right)$ are:

$$E\left(w^{it}\right)=\int\int w\cdot Pr\left(w,q\middle|p^{it},q^{it-1},z^{it},x^{it},\hat{\theta}\right)dwdq, \tag{G1}$$

$$E\left(q^{it}\right)=\int\int q\cdot Pr\left(w,q\middle|p^{it},q^{it-1},z^{it},x^{it},\hat{\theta}\right)dwdq. \tag{G2}$$

We use the observed quantities w^{it} and q^{it} ±10 million m³ per year as the ranges for the numerical integrations; each range is partitioned 100 times. Likewise, the expected probability that the price binds the village's water usage is:

$$E\left(Pr\left[D\left(p^{it},z^{it}\right)\leq q^{it}\right]\right)=\int\int Pr\left(w,q\middle|w\leq q,p^{it},q^{it-1},z^{it},\theta\right)dwdq, \tag{G3}$$

in which the probability $Pr\left(w,q\middle|w\leq q,p^{it},q^{it-1},z^{it},\hat{\theta}\right)$ is based on the first element of the bivariate likelihood function (Eq. 15):

$$Pr\left(w,q\middle|w\leq q,p^{it},q^{it-1},z^{it},\hat{\theta}\right)=\text{¿}\,Pr\left[\gamma^{it}+\varepsilon^{it}=w-D\left(p^{it},z^{it},\hat{\theta}\right),\gamma^{it}\leq q-D\left(p^{it},z^{it},\hat{\theta}\right),u^{it}=q-q^{it-1}\right]. \tag{G4}$$

The expected VMP for a village whose quota binds its water usage is:

$$E\left(\pi_w^{it}\middle|D\left(p^{it},z^{it}\right)>q^{it}\right)=\frac{\int\int\pi_w^{it}(q)\cdot Pr\left(w,q\middle|w>q,p^{it},q^{it-1},z^{it},x^{it},\hat{\theta}\right)dwdq}{1-E\left(Pr\left[D\left(p^{it},z^{it}\right)\leq q^{it}\right]\right)}, \tag{G5}$$

in which $\pi_w^{it}(q)=a\,z^{it}-bq$ (recall Eq. 9) is the VMP of the village whose quota q binds the water usage, and in which $Pr\left(w,q\middle|w>q,p^{it},q^{it-1},z^{it},x^{it},\hat{\theta}\right)$ is the probability that a village is bound by the quota; this probability relies on the second element of Eq. (15):

$$Pr\left(w,q \middle| w>q,p^{it},q^{it-1},z^{it},x^{it},\hat{\theta}\right)=\text{¿}\,Pr\left[\varepsilon^{it}=w-w,\gamma^{it}>w-D\left(p^{it},z^{it}\right),u^{it}=w-Q\left(p^{it},x^{it},z^{it}\right)\right].$$

(G6)

Consequently, the expected VMP at the consumption level is:

$$E\left(\pi_w^{it}\right)=p^{it}E\left(Pr\left[D\left(p^{it},z^{it}\right)\leq q^{it}\right]\right)+\text{¿}\int\int\pi_w^{it}(q)\cdot Pr\left(w,q \middle| w>q,p^{it},q^{it-1},z^{it},x^{it},\hat{\theta}\right)dwdq\,.$$

(G7)

Finally, the expected deadweight loss $E\left(DWL^{it}\right)$ is given by:

$$E\left(DWL^{it}\right)=\text{¿}\frac{1}{2b}\left[\left(c_w^{it}-p^{it}\right)^2E\left(Pr\left[D\left(p^{it},z^{it}\right)\leq q^{it}\right]\right)+\text{¿}\int\int\left(c_w^{it}-\pi_w^{it}(q)\right)^2\cdot Pr\left(w,q \middle| w>q,p^{it},q^{it-1},z^{it},x^{it},\hat{\theta}\right)dwd\right.$$

(G8)

G.2 A Simulation of an Equilibrium under a Quotas-Only Regime

We simulate the quotas-only policy by substituting $p^{it}=0$ in Eqs. (G1)–(G8). Consequently, the probability that the price binds the village's water usage becomes practically zero, and the expected VMP approaches $\frac{c_w^{it}}{1+\alpha}$ for every village *i* and time *t* .

G.3 A Simulation of an Equilibrium under a Price-Only Regime

To compute the regionally uniform price under an equilibrium in a price-only regime, we use Eq. (17), which (based on our linear specifications) becomes:

$$p_{jt}^{pe}=\frac{\bar{c}_w^{jt}-\alpha\phi\,\bar{a}_{jt}}{1-\alpha\phi}, \tag{G9}$$

in which $\bar{c}_w^{jt}$ and $\bar{a}_{jt}$ are the regional average marginal costs and the estimated intercept of the linear VMP function, respectively. To compute the various elements of the equilibrium, we substitute p_{jt}^{pe} in Eqs. (G1)–(G8), and hold q at its upper limit of the numerical integration; consequently, the probability of the quota being the binding factor virtually vanishes.

To obtain the price-only equilibrium, in the hypothetical case that prices were specifically set to each village, we substitute in Eq. (G9) the village-specific marginal cost c_w^{it} and the intercept a_{it} to obtain:

$$p_{it}^{pe}=\frac{c_w^{it}-\alpha\phi\,a_{it}}{1-\alpha\phi}. \tag{G10}$$