Illegal groundwater pumping

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Abstract

Aquifer overexploitation is a serious problem in many regions, although many existing models of groundwater management find small differences between optimally-managed aquifers and myopic common-property solutions. The reasons for this paradox are manifold but it is becoming clear that illegal extractions can be a significant stumbling block on the path towards the implementation of better management policies. In this paper we develop a model of illegal pumping for irrigation in a setting where there are productivity differences among farmers, with and without environmental externalities. We also discuss policy options when economic and social penalties affect compliance.

Keywords: groundwater management, legal vs. illegal use

1 Introduction

Plenty of the world's usable water is stored in groundwater reservoirs, which are typically common-property assets since water can be pumped by all those

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who own the land above an aquifer. There is clear potential for resource overexploitation, since each individual may pump without taking into consideration the impacts on other users and on future stock levels. Nonetheless, many studies that quantify the welfare losses associated with such myopic common property solutions find that the value of these losses may be fairly small, so that the potential gains from intervention are negligible. This result is known as the Gisser-Sánchez effect, after the well-known paper those two authors published in 1980 [8]. Koundouri [11] provides a review of the issues, noting that a number of factors may increase the welfare gains from intervention, including heterogeneous land productivity [23], and environmental externalities, among others.

Indeed, groundwater overdraft has been identified as an important driver for the disappearance of wetlands in many locations around the world. The Millennium Assessment Synthesis on Wetlands and Water ([17]) points out that "more than 50% of specific types of wetlands in parts of North America, Europe, Australia, and New Zealand were destroyed during the twentieth century, and many others in many parts of the world degraded." In turn, many wetlands are linked to aquifers. Spanish data, for instance, indicates that over 50% of identified wetland areas depend to a large extent on groundwater circulation and quality patterns. Moreover, these are precisely the wetlands where the most significant degradation has occurred. Since wetlands are characterized by high biological productivity, their loss entails significant impacts on biodiversity conservation, as well as the loss of valuable ecosystem services ([7], [17]). The FAO [6] also draws attention to the role of agriculture in the deterioration of water-related habitats.

Iglesias [10] extends the analytical framework of the Gisser-Sánchez model to argue that optimal groundwater management policy may yield very significant gains when environmental externalities are present. This author analyzes the emblematic case of the Western La Mancha aquifer in Spain, where years of aquifer overexploitation have led to significant drops in water-table levels, leading to severe degradation of the "Mancha Húmeda" Biosphere Reserve ([16]). The Tablas de Daimiel wetland, located in the area, has repeatedly exhibited dry patches and in 2009 suffered its most recent episode of spontaneous combustion caused by lack of water.

Esteban and Albiac [5] develop a model of groundwater management with environmental externalities which is applied to the Eastern and Western La Mancha aquifers, highlighting the important role of institutional arrangements. However, the paper does not explicitly consider two inherent difficulties present in Western La Mancha: first, the presence of an environmental effect complicates water-management policies as environmental costs fall outside the limited scope of the common-property users; second, the issue of illegal wells is paramount in the aquifer and it is not present in the model.

Unauthorized water use is, in fact, a key issue to understand many of the problems related to depleting and overexploited stocks. The difference between farm value-added when irrigation is applied and when it is not is extremely high: Maestu and Gomez [14] point out that "the income from a typical irrigated hectare is six times greater than that of an average rainfed hectare", so there is a strong economic incentive for farmers to water their crops whether or not they are allowed to do so. In the Western La Mancha, for example, Martinez-Santos et al [16] cites official estimates which indicate that half of all existing wells may be illegal. De Stefano and Lopez-Gunn [3] describe several typologies of unauthorized groundwater use, including new wells drilled in aquifers that are supposed to be "closed" due to overexploitation, abstraction performed while waiting for a license, abstraction of a volume that is higher than the established limits and unreported modifications in wells. Data from Dworak et al [4] suggests that in several Southern European countries unauthorized abstraction may account for 30-60% of total abstractions in agriculture.

Some authors have recently begun to analyse the problem of non-compliance with resource management regimes, based on the literature on social norms in common property resource use pioneered by Ostrom [20]. Examples can be found in industrial pollution [22], fisheries ([1], [9]), and forests [21]. Nøstbakken [18] presents a general model of renewable resource use with formal and informal enforcement, where the dynamic relations between the two are emphasized. Oses-Eraso and Viladrich-Grau [19], on the other hand, provide an evolutionary framework for common property resource management where agents either cooperate or not and their behaviour changes in response to varying pay offs. Marchiori et al [15] develop a static model where unauthorized water pumping in the Guadiana basin is analysed numerically in a Nash bargaining framework, with the national government setting the structure, local stakeholders selecting policy instruments and farmers responding to these instruments. Furthermore, Lopez-Gunn and Martinez-Cortina [13] note that although self-regulation by users under collective arrangements is to be encouraged, "one cannot be blinded by self-regulation, since it still needs to be backed up by a strong and clear regulatory regime, should self-regulation fail." Finally, Liu et al [12] discuss the relevance of the entry decision, in addition to that of abstraction volumes, in an experimental setting.

In this paper we develop a dynamic model of water abstraction in an aquifer where farms have different productivities and only some users are authorized to pump. We extend the analysis to environmental externalities and analyse policy options, analysing the entry decision as well as that of water abstraction volumes. The following section contains the basic farmer model, while Section 3 discusses the different options available to the water regulator. Section 4 concludes.

2 Basic user model

The basic model of groundwater quantity management consists of a dynamic equation for the water table and a set of net benefits from groundwater use. We will consider only the case of water pumped for irrigation, which accounts for a significant part of groundwater extractions (around 75% in Spain, according to Custodio et al. [2]) Stock dynamics are assumed to be given by the traditional expression for a single-cell aquifer:

$$\dot{H}_t = \frac{R - (1-\alpha)W_t}{AS} \tag{1}$$

where W_t is total water use as defined in equation (3) below, natural recharge is denoted by R, the return flow coefficient is α, and AS is the area of the aquifer multiplied by storativity.

To explore the implications of considering legal and illegal water use in the next sections, we allow for three groups of farmers, or rather three groups of lands. We will denote by x_l, with $l = 1 \dots L$, the farming lands where irrigation is done with a permit and farmers pump "legal water", whereas x_i, with $i = 1 \dots I$, will refer to those irrigated lands whose farmers are not authorized to pump but still do so, which we call "illegal water". We are thus focusing on a particular type of unauthorized use, that of new unlicensed wells. Finally we name x_d, with $d = 1 \dots D$, existing dry-land farms which could potentially become illegal, that is, farmers with land in group d can move to group i.

In each period t the sum of all three groups' farms will amount to the total farming land in the area, which is constant:

$$\sum_l x_{lt} + \sum_i x_{it} + \sum_d x_{dt} = X_T \tag{2}$$

As far as water use is concerned, in equation (3) we define total water use as the sum of legal water pumped by group x_l, which includes those lands for which pumping is officially allowed within levels established by a water regulator, and illegal water pumped by group x_i, which contains lands that have no well permissions.

$$\sum_l x_{lt} w_{lt} + \sum_i x_{it} w_{it} = W_t \tag{3}$$

The expression for the net benefits obtained from production from one unit of land by a given farmer, dropping time subscripts to ease notation, is:

$$NB_k = F_k(w_k) - C_k(w_k, H) \tag{4}$$

where $F_k(w_k)$ for $k \in i, l$ is the benefit of water use assuming that other production variables are optimized, and $C_k(w_k, H)$ is the cost of water pumping, which will depend on the amount of water pumped by the user of type k, w_k, as well as on the height of the water table, H, because as the water table sinks deeper, pumping costs should increase. If all farmers were alike their pumping decisions would also be similar, i.e. either no one would pump or everyone would, and at the same rate. Both benefit and cost functions could be different in equation (4) However, we will assume that only the benefit function varies, in order to explore heterogeneous productivity, for example due to varying soil quality. For that goal we will introduce a parameter β to indicate productivity differences, that is $F_k(w_k) \equiv F(w_k, \beta)$. We expect the usual properties to hold, namely:

- On production benefits: the marginal benefit of using water is non-negative but decreasing $\frac{\partial F}{\partial w_k} \geq 0$, $\frac{\partial^2 F}{\partial w_k^2} \leq 0$, and the higher β the larger the marginal benefit of water, with $\frac{\partial F}{\partial w_k} = 0$ for $\beta \leq \underline{\beta}$. All variables are non-negative and $F(0, \beta) = F_d$ is the benefit attained by dry-land farmers;

- On pumping costs: the marginal cost of pumping water is non-negative and increasing $\frac{\partial C}{\partial w_k} \geq 0$, $\frac{\partial^2 C}{\partial w_k^2} \geq 0$, whereas the effect of the water-table height can be summarized by $\frac{\partial C}{\partial H} \leq 0$, $\frac{\partial^2 C}{\partial H^2} \geq 0$, $\frac{\partial^2 C}{\partial w_k \partial H} \leq 0$. Since dry-land farmers use no water, $C_d = 0$.

If there was no regulating agency overlooking the aquifer and management of the resource was entirely left to individual farmers making their profit-maximizing choices, we would only distinguish irrigators from dry-land farmers, as there would be no distinction between legal and illegal use. In this case, dry-land farms would be only those for which β is too low to warrant using irrigation equipment. From the point of view of the aquifer, therefore, only the behavior of farmers with a sufficiently high productivity parameter, $\beta \geq \underline{\beta}$, would matter, because they would be the ones irrigating their crops. It makes sense to assume that individual farmers would be myopic, not taking aquifer dynamics into account, whenever there are a large number of users and each has a negligible impact on the aquifer. That myopic behavior by such farmers leads to a smaller aquifer than would be optimal is a well-known result in the literature (in fact, this is the result Gisser and Sanchez discuss the practical relevance of, using specific functional forms).

First-order conditions for the myopic maximization problem yield:

$$\frac{\partial F}{\partial w} = \frac{\partial C}{\partial w} \tag{5}$$

Condition (5) implicitly defines the desired level of water use by each farmer, $w_{\beta}*$. Given the assumptions on $F(\cdot)$ and $C(\cdot)$, farmers will pump more if their level of β is higher and less if the height of the water table is lower. For each H we can find the level $\underline{\beta}$ for which a farmer would be indifferent between pumping and not pumping, using:

$$F(0, \underline{\beta}) = F(w^*, \underline{\beta}) - C(w^*, H) \tag{6}$$

As long as $\frac{\partial F(w^*)}{\partial \underline{\beta}} > \frac{\partial F(0)}{\partial \underline{\beta}}$, an increase in the water table level will lower the value of productivity that makes it worth pumping, as expected.

If recharge is constant, a steady state will be reached whenever $\dot{H} = 0$, so the overall amount of water extracted must be $W = \frac{R}{1-\alpha}$, which is independent of the institutional framework and of all other model parameters. This is a common result in groundwater management models and will be used in the next sections to provide some comparisons between the regulated and unregulated solutions.

3 Regulator model

Now, suppose that a water regulator does exist and wishes to define whether users can pump and how much. We begin by presenting the case of the social planner who has perfect information, establishes optimal policies and expects them to be implemented as decided. In subsection 3.1 all users are treated alike as there is no a priori reason to favor some over others and optimal quotas will depend only on model parameters. In subsection 3.2 the distinction between legal and illegal users will be introduced.

3.1 A social planner

The optimal control problem for groundwater management taking into consideration all farmers, where water abstractions are the control variables and aquifer height is the state variable, can be written as:

$$\max \quad \int_0^\infty e^{-rt} \left[\sum_\beta x_{\beta t} \left(F(w_t, \beta) - C(w_t, H) \right) \right] dt \tag{7}$$

subject to equations (1), (2) and (3). The corresponding Hamiltonian is

$$\mathcal{H} = e^{-rt} \left[\sum_\beta x_{\beta t} \left(F(w_t, \beta) - C(w_t, H) \right) \right] + \lambda_t \left(\frac{R - (1-\alpha) W_t}{AS} \right)$$

If there is a finite number of soil types, the summation over users is finite, so we can reformulate the problem as a finite sum of integrals. The regulator problem for the generic users of type β is (in current–value terms and dropping time subscripts):

$$\mathcal{J} = x_{\beta t} \left(F(w_\beta, \beta) - C(w_\beta, H) \right) + \mu \left(\frac{R - (1-\alpha) W}{AS} \right)$$

Noting that $W = \sum\limits_\beta x_\beta w_\beta$, the above problem yields the following first–order conditions:

$$\frac{\partial F}{\partial w_\beta} - \frac{\partial C}{\partial w_\beta} = \mu \left(\frac{(1-\alpha)}{AS} \right) \tag{8a}$$

$$\dot{\mu} - r\mu = \frac{\partial C}{\partial H} \tag{8b}$$

$$\dot{H} = \frac{R - (1-\alpha) W}{AS} \tag{8c}$$

Again, for a stationary solution, $\dot{H} = 0$, so the overall amount of water extracted is $W = \frac{R}{1-\alpha}$, as in the myopic case. However, from equation (8a), $\frac{\partial F}{\partial w} > \frac{\partial C}{\partial w}$ for a given β. If the same farmers were pumping here than in the myopic case, that is, if the $\underline{\beta}$ was the same, this could be compared with equation (5) to show that marginal extraction costs were necessarily lower, so that the height of the water table would be higher now. However, in the heterogeneous case this cannot be guaranteed, as a fuller aquifer creates the conditions for more farms to be brought into irrigation. At any rate, equation (8a) indicates that for different values of β, such as $\beta_1 \geq \beta_2$, the higher-productivity farmers will optimally be allowed to pump more water per unit of land. The regulator could alternatively select a price policy, charging a water tax $t = \mu\left(\frac{(1-\alpha)}{AS}\right)$, which would be the same for all farmers and may be simpler than setting variable quotas.

Differentiation of (8a) with respect to time and rearranging together with (8b) yields the following:

$$\frac{\partial C}{\partial H} = \frac{AS}{(1-\alpha)}\left(\frac{\partial^2 F}{\partial w^2} - \frac{\partial^2 C}{\partial w^2}\right)\dot{w} - \frac{rAS}{(1-\alpha)\left(\frac{\partial F}{\partial w} - \frac{\partial C}{\partial w}\right)} \tag{9}$$

In the steady state $\dot{w} = 0$ and $\dot{H} = 0$, therefore after rearranging terms, the optimal extraction is given implicitly by

$$\frac{\partial F}{\partial w} = \frac{\partial C}{\partial w} - \frac{(1-\alpha)}{rAS}\frac{\partial C}{\partial H} \tag{10}$$

The right–hand–side of equation (10) represents the sum of private and social costs of extraction. The second term, which is negative since by assumption $\frac{\partial C}{\partial H} < 0$, shows the impact of pumping on future costs through lower aquifer height.

If we introduce environmental damage caused by insufficient water in the aquifer, $D(H)$ with $\frac{\partial D}{\partial H} < 0$, the distinction between the myopic solution and the optimal one is even starker. The extra damage would enter the maximand in (7), leading to an alternative version of condition (8b): $\dot{\mu}_t - r\mu = \frac{\partial C}{\partial H} + \frac{\partial D}{\partial H}$. The additional cost embodied in $\frac{\partial D}{\partial H} < 0$ implies a larger optimal size for the aquifer, taking it further from the myopic level. For this new case, the regulator should again define quotas or taxes. We expect the latter to be harsher than those of the previous model. In the following section, environmental externalities will not be considered since the overall results would be similar, albeit with lower welfare outcomes.

3.2 The naive regulator

Up to this point we have assumed that the regulator treats all water users alike. However, in reality many aquifers have users who are legally entitled to pump and others who are not, normally for historical reasons associated with the attribution of pumping rights. If the regulator sets water quotas based on legal users only and ignores the existence or behavior of the illegal users, outcomes can be far from the desired optimum. Suppose in particular that w_l is exogenously established by the naive regulator in a suboptimal form, authorizing a certain quota or water allotment to legal farms in a way that distributes available renewable resources equally, ignoring productivity differences, as expressed in equation (11). The average value of recharge is used to define allowed extraction. Legal users have compulsory measurement equipments in their wells and so will not overstep their quotas, but will presumably wish to exhaust their water allotments, so marginal net returns on legal irrigation activities must be strictly positive.

$$w_l = \frac{R}{(1-\alpha)\sum x_l} \tag{11}$$

If there were no illegal uses, this would ensure a stationary solution for the water table. However, illegal use does occur and this can be represented as an endogenous choice driven by the returns on pumping activity. We expect illegal farmers to behave myopically and pump water to maximize their short-term benefits in each period, considering production costs and benefits as before but also the penalties associated with illegal behaviour, as expressed by the objective function (12). We describe with a rationality constraint, in (13), that this strategy will only be pursued if the reward of illegal activities overtakes that of complying with the law and maintaining a dry-land cropping pattern, i.e. remaining in group x_d.

$$\max_{w_i} \quad NB_i = F(w_i,\beta) - C(w_i,H) - P(p^e, w_i, \phi) - p^s(X_T) \tag{12}$$

$$s.t. \quad NB_i \geq NB_d \tag{13}$$

where $NB_d = F_d = F(w_i = 0, \beta)$ is the benefit a farmer would have if there is no irrigation.

The benefit function for the group of illegal farmers in (12) considers not only the economic value of water but also the extra cost related to forbidden activities, i.e. the farmer takes into consideration that he may be inspected and face an economic penalty, P. The economic penalty function could be linear in extraction, for example $P(p^e, w_i, \phi) = \phi(X_T)w_i p^e$ where ϕ is the enforcement intensity, which should decrease as the size of the farming area X_T, increases, because the likelihood of getting caught is smaller. We assume that X_T is exogenous, because there is a fixed amount of land over the aquifer. However, as noted below, the economic penalty function should also depend on the overall level of the aquifer, otherwise optimal deterrence will not be achieved.

As in Nøstbakken [18], we postulate that there is also a social sanction, p^s, that the community exerts on illegal behaviour, which embodies an intrinsic or moral cost for the farmer. Although this is not a direct monetary cost, we assume that p^s represents the monetary value of the farmer's disutility. Note that this social sanction is not linked to probabilities of inspection since it is assumed that the neighbours have enough information about farming activities. The strength of the social sanction could be expected to depend on the importance of illegal use. In particular, the social penalty would be larger if most farmers comply with the law and smaller if many farmers were to become illegal. Since the number of illegal users is endogenous, however, such a specification complicates the problem significantly, so an alternative is for the social penalty to depend of the overall size of the farmed land – assuming that larger aquifers will hold more farms. [1]

According to equation (13), the payoff associated with becoming an illegal farmer, δ, can be written as:

$$\delta = F(w_i, \beta) - F(w_i = 0, \beta) - C(w_i, H) - P(p^e, w_i, \phi, H) - p^s(X_T) \quad (14)$$

[1] Esteban and Albiac (2011) point out that one of the difficulties in the overexploitation of the Western La Mancha aquifer is the large number of users - around 70,000, many of them illegal. This means the likelihood of getting caught is low, as is any potential social penalty.

That is, there will be illegal irrigation if the additional productivity gained from watering crops $F(w_i, \beta) - F(w_i = 0, \beta)$ is higher than the sum of extraction costs with economic and social penalties.

Legal use is constant and given by equation (11), since no more water entitlements are given by the administration, while illegal use will depend on the payoff defined in equation (14) above. First-order conditions for the myopic maximization problem of illegal farmers yield, if $\delta > 0$:

$$\frac{\partial F}{\partial w} = \frac{\partial C}{\partial w} + \frac{\partial P}{\partial w} \tag{15}$$

Although total land is constant (equation (2)), there may be movements between groups, and there will also be initial conditions for H and x_k. Equation (15) shows that once the dry-land farmer decides to start irrigating the choice of how much water to extract does not depend on the social sanction p^s. The economic sanction, on the other hand, reduces desired water use because it is an additional marginal cost. It is important to point out that the farmer's myopic solution only has a stationary equilibrium if the pumping cost externality (i.e. the increase in costs due to a falling water level) is strong enough to take δ to zero, leading to a stop in illegal extractions. Otherwise, since legal extractions are designed to exhaust the natural recharge in each period, the existence of illegal extractions means that the water level will keep falling – possibly until the total collapse of the aquifer, damaging production possibilities for both legal and illegal users. On the other hand, if a stationary equilibrium exists it will not be optimal unless the economic penalty is made dependent on the water table (compare equations (15) and (10)).

If the regulator distinguishes between legal and illegal users, it can set a quota for the former and an economic penalty for the latter that leads them to stop abstraction. However, a truly insightful regulator would take into consideration the social penalty as well, and perhaps even acknowledge that the social penalty can be endogenous (see [18]), although the dynamic groundwater model would become much harder to solve. If, on the other hand, the regulator only sets quotas for legal users and provides no instruments to control illegal users, the drop in the water table caused by the miscalculation could lead legal quotas to drop over time (see equation 10) . Eventually illegal users will "crowd out" the legal ones, yielding again the myopic solution. This naive behavior may be unrealistic, but it provides a possible description of how some water authorities have acted in the past, thus allowing the continuing aquifer overexploitation.

Finally, the model can be extended to allow those who were extracting illegally, or any dry-land farm (that is, x_i and x_d) to become legal users for example by setting up a water market where legal quotas can be bought and sold. Thus now farmers in groups i and d can move to group l; however, farmers in d may still move to i. We would thus add an incentive constraint that establishes that rewards of being illegal exceeds those obtained buying water in the market to legally turn their lands into irrigation. With water markets allowing purchases by all farmers, the new constraint for illegals would be $NB_{it} \geq NB_l$ where $NB_l = F(w_{it}, p^w, \beta)$ and p^w is the market price of water. Trade among water users will be driven by productivity differences, since those with higher productivity will want to purchase extra water above their quota and those with lower productivity would rather sell.

4 Conclusion

In this paper we create a model of groundwater management that explicitly recognizes the existence of distinct groups of players, namely legal and illegal water users. Further, we acknowledge that there are productivity differences among users. We assume that legal users follow water policy restrictions, namely the quotas set for them by the regulator, while those who do not have extraction permits will either remain dry-land farmers or become illegal water users. Their decision will come from a profit-maximization problem under an incentive compatibility constraint which determines whether illegal extraction is worth it. We show that the optimal aquifer size is larger than that achieved by myopic users, noting that in the latter case a naive regulator, setting quotas based on recharge, may lead to aquifer collapse. The latter result yields an even more disturbing conclusion whenever farmers without pumping permits are productive as well as when the differences in productivity between them are high.

In the presence of environmental externalities, the difference between the two settings is even larger. As the non-compliance problem is very relevant in many aquifers, some of which are critically overexploited, we believe our model is a significant contribution to the groundwater management literature. Further research will focus on developing an empirical application, exploring formulations for the various policy instruments, and developing the links between formal and informal penalties.

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