Illegal groundwater pumping

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January 2014

Abstract
Aquifer overexploitation is a serious problem in many regions. Most existing models minimize the difference between optimally managed aquifers and common property myopic solutions by not considering the environmental consequences of aquifer overexploitation. Moreover, it is becoming clear that illegal extractions are 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 soil-productivity differences, 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 who own the land above an aquifer. There is clear potential for resource

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overexploitation, since each individual will 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-Sanchez effect, after the well-known paper those two authors published in 1980 (Gisser and Sanchez 1980). Koundouri (2004) provides a review of the issues, while discussing some political economy aspects that are often overlooked, such as bargaining processes, information deficiencies and high transaction costs.

Although for some areas it may be true that the impact of excessive pumping on common-property users, through a pumping cost externality, is not very large, the problem of optimal management is different when there are environmental externalities associated with groundwater overdraft. In particular, groundwater extraction 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 (MEA 2005) 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 Mediterranean countries, such as Spain, Italy, and Greece, the loss of these ecosystems has exceeded 60% (Barbier et al. 1996). In turn, many wetlands are linked to aquifers. Spanish data, for instance, indicates that over 50% of identified wetland areas are related to groundwater and thus depend to a large extent on its 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 (Gibbs 2000, MEA 2005).

Iglesias (2002) extends the analytical framework of the Gisser-Sanchez 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 (Martinez-Santos et al. 2008). The Tablas de Daimiel wetland, located in the area, has exhibited repeatedly dry patches and in 2009 it suffered its most recent episode of spontaneous combustion caused by lack of water.

Esteban and Albiac (2011) 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 that are 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. Illegal 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 (2010) indicate that "the income from a typical irrigated hectare is six times greater than that of an average rainfed hectare", so it is very profitable for farmers to water their crops. In the Western La Mancha, for example, Martinez-Santos et al. (2008) cite official estimates which indicate that half of all existing wells may be illegal. Marchiori et al. (2012) recognize the problem and use the Guadiana basin to develop a Nash bargaining framework where the national government sets the structure, local stakeholders select policy instruments and farmers respond to these instruments. Empirical evidence demonstrates that illegal activities, including unlicensed water extraction, illegal logging and pollution discharges, are at the root of the degradation of water-related habitats. FAO (2008) calls attention to the role of agriculture in the deterioration process.

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 (1990). Examples can
be found in industrial pollution (Pargal and Wheeler 1996), fisheries (Agniew et al, 2009; Hatcher and Gordon 2005), and forests (Palmer, 2000). Nostbakken (2011) 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 (2007), 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.

In this paper we develop a model of illegal pumping in an aquifer where farms have different productivities. We extend the analysis to environmental externalities and analyse policy options. 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. 2010) Stock dynamics are assumed to be given by the traditional expression for a single-cell aquifer:

\[
\frac{\dot{H}_t}{H_t} = \frac{R - (1 - \alpha)W_t}{AS}
\]  

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

To explore the implications of considering legal and illegal water use, we define three groups of farmers. We will denote by \(x_l\), with \(l = 1 \ldots L\), the farming lands of irrigation farmers who have a permit and pump "legal water", whereas \(x_i\), with \(i = 1 \ldots I\), will refer to those irrigation lands whose farmers are not authorized to pump but still do so, which we call "illegal
water”. Finally we name \( x_d \), with \( d = 1 \ldots D \), existing dry-land farms which could potentially become illegal, that is, farmers 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:

\[
\sum_l x_{lt} + \sum_i x_{it} + \sum_d x_{dt} = X_T
\]

(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.

\[
\sum_l x_{lt} w_{lt} + \sum_i x_{it} w_{it} = W_t
\]

(3)

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

\[
NB_k = F_k(w_k) - C_k(w_k, H)
\]

(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. Note that the benefit and cost functions could be different for \( i \) and \( l \). To simplify, we will assume that only the benefit function varies, and we will introduce a parameter \( \beta \) 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 \( \beta \) the larger the marginal benefit of water, with \( \frac{\partial F}{\partial w_k} = 0 \) for \( \beta \leq \beta \) and higher
marginal productivity of water for higher values of $\beta$. All variables are non-negative and $F(0, \beta) = F_d$ is the benefit attained by dry-land farmers;

- On production 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 water users from dry-land farmers, where the latter would be those for which $\beta$ is too low to warrant using irrigation equipment. Note that from the point of view of the aquifer, only the behaviour of farmers with a sufficiently high productivity parameter, $\beta \geq \beta_*$, would matter, because they would be the ones irrigating their crops. It makes sense for the individual farmer to be myopic if there is a large number of users and each has a negligible impact on the aquifer. That myopic behaviour 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:

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

(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 $\beta$ is higher and less if the height of the water table is lower. For each $H$ we can find the level of $\beta$ for which a farmer would be indifferent between pumping and not pumping, using:

$$F(0, \beta) = F(w^*, \beta) - C(w^*, H)$$

(6)

If recharge is constant, the steady state will be reached whenever $\dot{H} = 0$, so the overall amount of water extracted must be $W = \frac{R}{1-\alpha}$. Moreover, the
existence of environmental externalities associated with groundwater stocks, which are not taken into consideration by the individual users, drives the myopic solution further from the optimal state, as shown in the next section.

3 Regulator model

Now, suppose that a water regulator does exist and that it 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. All users are treated alike as there is not a priori reason to favour some over others and optimal quotas will depend only on model parameters.

3.1 A social planner

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

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

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

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

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 user of type $\beta$ is (in current-value terms and dropping time subscripts),

$$J = F(w_{\beta}, \beta) - C(w_{\beta}, H) + \mu \left( \frac{R - (1 - \alpha)W}{AS} \right)$$
Noting that \( W = \sum_{\beta} x_\beta w_\beta \), the above problem yields the following first-order conditions:

\[
\frac{\partial F}{\partial w_\beta} - \frac{\partial C}{\partial w_\beta} = \mu \left( \frac{(1 - \alpha)x_\beta}{AS} \right) \\
\dot{\mu} - r\mu = \frac{\partial C}{\partial H} \\
\dot{H} = R - (1 - \alpha)W \quad \text{AS}
\]  

(8a)  

(8b)  

(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), \( \frac{\partial F}{\partial w} > \frac{\partial C}{\partial w} \). Given the same level of extraction, this can be compared with Equation (5) to show that marginal extraction cost is necessarily higher in the myopic case, so that the height of the water table is lower. Moreover, considering different values for \( \beta \), such as \( \beta_1 > \beta_2 \), it is possible to see from (8a) that if \( x_{\beta_2} \leq x_{\beta_1} \), then the higher-productivity farmers will optimally be allowed to pump more water per unit of land.

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

\[
\frac{\partial C}{\partial H} = \frac{AS}{(1 - \alpha)x_\beta} \left[ \left( \frac{\partial F}{\partial w^2} - \frac{\partial^2 C}{\partial w \partial H} \right) \dot{w} - \frac{\partial^2 C}{\partial w \partial H} \dot{H} \right] - \frac{rAS}{(1 - \alpha)x_\beta} \left( \frac{\partial F}{\partial w} - \frac{\partial C}{\partial w} \right)
\]

(9)

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

\[
\frac{\partial F}{\partial w} = \frac{\partial C}{\partial w} - \frac{(1 - \alpha)x_\beta}{rAS} \frac{\partial C}{\partial H}
\]

(10)

The right-hand-side of Equation (10) represents now 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 $\partial D/\partial H < 0$, the distinction between the myopic solution and the optimal one is even starker. The extra damage would enter the maximand in (12), leading to an alternative version of condition (8b): $\dot{\mu}_t - r\mu = \partial C/\partial H + \partial D/\partial H$. The additional cost embodied in $\partial D/\partial H < 0$ implies a larger optimal size for the aquifer, taking it further from the myopic level.

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 behaviour of the illegal users, outcomes can be far from the desired optimum. Suppose in particular that $w_l$ is exogenously established by the regulator, who authorizes 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). We let the quotas be constant for simplicity, using the average value of recharge to define allowed extraction. Legal users have compulsory measurement equipments in their wells and so will not overstep their quotas.

$$w_l = \frac{R}{\sum x_l} \quad (11)$$

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 that is 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 \( x_d \).

\[
\begin{align*}
\max_{w_i} & \quad NB_i = F(w_i, \beta) - C(w_i, H) - P(p^e, w_i, \phi) - p^s(X_T) \\
\text{s.t.} & \quad NB_i \geq NB_d
\end{align*}
\] (12)

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 \( P(p^e, w_i, \phi) = \phi(X_T)w_ip^e \) where \( \phi \) 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.

As in Nostbakken (2011), 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.

According to Equation (13), the payoff associated with becoming an illegal farmer, \( \delta \), can be written as:

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

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 $\delta > 0$:

$$\frac{\partial F}{\partial w} = \frac{\partial C}{\partial w} + \frac{\partial P}{\partial w}$$  \hspace{1cm} (15)

Again, similarly to Eq. (6), we can use (15) to find the level of productivity $\hat{\beta}$ below which the farmer decides not to pump. With the distinction between legal and illegal pumping, it is easy to see that $\hat{\beta} > \beta$, and that since solution to (15) prescribes a lower optimal extraction for those who actually start pumping than (5), the overall extraction is lower than in the myopic model.

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 $\delta$ 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 regulator adjusts the quotas for legal users and 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 will take into consideration the social penalty as well, and perhaps even acknowledge that the social penalty can be endogenous (see Nostbakken, 2011), although the dynamic groundwater model would be become much less tractable.

Notice a paradoxical result which arises from comparison of the ”naive regulator” and the social planner. If the regulator is, indeed, so short-sighted, that he simply sets constant quotas (as specified in Eq. (11)), solution to
shows that the overall water use decreases. However, if he sets quotas dynamically according to solution to (10), at the same time not being able to enforce the socially optimal behavior of the illegal users, the quotas decrease over time because of the effect on \( H \) imposed by the illegal users. Eventually, the legal quotas would drop to zero, and the extraction will be fully "crowded out" by the illegal users leading to the myopic solution! This naive behavior may sound 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 that incorporates both economic and social penalties and where there is an incentive compatibility constraint which determines whether illegal extrac-
tion 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.

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 empirical applications, exploring quota enforcement, incentives for illegal users with and without water markets, and developing the links between formal and informal penalties.

References


