Chapter

On the Design of Total Water Use-Based Incentive Schemes for Groundwater Management

Wided Mattoussi, Mohamed Salah Matoussi and Foued Mattoussi

Abstract

Groundwater over-pumping by manipulating water meters may constraint the efficient use of the resource, leading to the potential aquifers' deterioration. Well designed institutional arrangements might be effective at reducing over-exploitation. The objective of this research was to shed light on the design of various incentive schemes to face groundwater over-pumping ranging from individual water use-based incentive schemes, where individual withdrawals are the users' private information, to total water use-based incentive schemes, where the aggregate withdrawal is publicly observable. For the latter setting, two schemes were proposed. The first one is within the framework of moral hazard in teams, where the Water Authority administers monetary incentives that do not balance the budget, restoring thereby the full-information outcome. The second scheme promotes a cooperative management governed by a collective responsibility rule that induces peer monitoring by members. We show that groundwater overuse is more likely when monitoring costs are high, punishments are weak and cooperatives are large. We also show how the cooperative size and punishments are determined endogenously by constraints on monitoring. We extend the basic analysis to study collusion in monitoring between cooperative members and compare different monitoring structures. The results confirm that well-designed incentives and institutions can reduce groundwater over-exploitation, and that constraints on monitoring costs affect institutional design.

Keywords: groundwater over-pumping, moral hazard in teams, cooperatives, peer monitoring, cooperative size, collusion, monitoring structure

1. Introduction

Groundwater resources are important for at least two reasons: Firstly, they are well appropriate for drinking[1] due to their (generally) high quality [2, 3]. Secondly, groundwater reservoirs constitute very important long-term storage [4–6], particularly useful during long periods of droughts characterizing arid and semi-arid regions.

1 Falkenmark [1] estimates that one-third of the world's population rely on groundwater supply for drinking.

The two major threats to groundwater are over-exploitation and pollution [7]. The rapid demographic growth, urbanization, industrialization, intensification of farming practices and climate change pressures have led to an increasing demand for groundwater as a reliable source of water supply.[2]

Intensive abstraction can deplete the groundwater in an aquifer. It might be possible to over-pump any aquifer temporary during periods of droughts, but durable over-exploitation would certainly lead to irreversible degradations [9], due for example to saline intrusion, sea water intrusion and quality deteriorations generated by declining water tables. The artificial recharge of aquifers is appealing, but it might not be implemented on a large scale, meaning that only the long-term natural replenishment guarantees the groundwater conservation. The only course left open is then a better management of the resource.

A large set of policy instruments have been developed for a better groundwater management, including economic instruments and institutional arrangements. Several economic instruments are used to limit over-exploitation such as water quotas, pumping taxes or marketable pumping permits. They however focus on individual withdrawals which are assumed to be publicly observable. This is rarely the case in the real world as legal and administrative settings are generally insufficient to perfectly monitor individual withdrawals, meaning that groundwater may present open-access resource features [10]. Groundwater is hence withdrawn in an imperfect informational context and the above instruments become ineffective.

Economists now agree on the fact that resource allocation in less developed economies is profoundly influenced by non firm institutions such as group lending, credit cooperatives, sharecropping, Water Users Associations and so forth. In developing countries various water institutions coexist. They range from centralized regulation, where management responsibility is entirely delegated to government agencies, to markets[3] for tradable water rights where farmers can sell their water shares to higher value uses. In between lies the entire spectrum of water allocation methods characterized by levels of decentralization, including Water Users Associations (referred to as water cooperatives), where users are involved in the decision-making process, and are thereby entrusted with part of the management responsibility normally held by government agencies. Water institutions can be effective at improving the resource allocation whenever they are well designed. Institutions influence individual behavior through incentives they give rise to, but institutions themselves evolve endogenously in part because of their incentive properties [11].

This paper sheds light on the design of various incentive schemes to face groundwater over-exploitation by farmers who can over-pump water typically by manipulating their individual water meters in an asymmetric information context.[4] In the sequel of this work, we refer to groundwater over-pumping as groundwater theft. The study in particular shows how the effective design of water institutions in response to a perceived problem of theft can help to reduce theft of water, and thereby improve water use efficiency. The response of the Water Authority (hereafter, WA), to tackle theft will differ according to whether it uses an incentive

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[2] Groundwater constitutes about 89% of the freshwater on our planet (discounting that in the polar ice caps) [8] (p.1).

[3] The most celebrated case of tradable water rights comes from Chile, where agrarian reforms and the Water Code of 1981 formalized water rights, and allowed for water sales separately from sales of land.

[4] Despite the relevance of asymmetric information problems for water management, only a few studies examine the application of such concepts to irrigation water in general and to irrigation groundwater in particular [12].

scheme based on the individual farmer's withdrawal which is her private information, namely the centralized management which dominated water management in developing countries for several decades [13] or it resorts to total water use-based incentive schemes, where the total amount of water withdrawn by farmers is publicly observable and payments from farmers can be conditioned on it.

In the centralized scheme, farmers who steal, do so directly from the WA, and thereby do not impose negative externalities on each other. The WA tries to reduce theft by directly monitoring the farmers' behavior, punishing observed instances of theft. We show in the model that some monitoring is always required in equilibrium. The WA tolerates some theft in order to save in monitoring costs.

In the decentralized management, where unobserved farmers withdrawals can be regulated through instruments based on collective performance (observed aggregate withdrawals) two schemes will be proposed. The first one corresponds to the framework of moral hazard in teams' problem where the WA administers incentive schemes that do not balance the budget, restoring thereby the full-information outcome [14]. Such scheme works independently of the team size, but it may be infeasible when farmers have endowment constraints. This is why one may resort to an alternative team-based incentive scheme that might not violate individual endowment constraints and in which the WA makes use of the informational advantages farmers have over the WA because of their long standing and high trade links (especially in close-knit societies). This corresponds to cooperative institutions which are very likely to be well suited to deal with a variety of collective action problems associated with water management, though their success in doing so depends on some particular features of their design. In this research we show that such institutions may also be well suited to dealing with groundwater theft; we discuss the features of their design that enable them to do so. We show that the incentives for theft vary considerably in response to these features and discuss implications for policy. We in particular consider the properties of cooperatives characterized by a collective responsibility rule, which makes all members jointly liable for aggregate withdrawals, and show that this feature is likely to induce peer monitoring by cooperative members[5] which is likely to be more effective at reducing theft than any means available to more centralized structures. We in particular show that groundwater theft is more likely when monitoring costs are high, punishment levels are weak and cooperatives are large. Moreover, straightforward comparison of the two team-based schemes shows that with sufficiently stringent punishments, the two schemes achieve the full-information water use level. Otherwise, theft occurs in cooperatives and a positive monitoring effort is required in equilibrium, meaning that the first team-based incentive scheme outperforms the cooperative management.

The results in the cooperative setting are obtained for given levels of punishment and cooperative size, but cooperatives are typically able to influence both of these variables. The model shows that these institutional characteristics are endogenously determined by constraints on monitoring: Higher monitoring costs increase punishment levels and reduce the cooperative size. Simulations also show that cooperatives can be neither too small because of the "monitoring costs savings" effect nor too large because of the "stealing" effect.

We extend the analysis thereafter to tackle the issue of collusion in monitoring efforts of cooperative members and show that collusion is welfare enhancing. We then compare among different monitoring structures, mutual and localized monitoring. Although in practice the mutual monitoring structure - whereby each farmer

[5] There is now a substantial literature on peer monitoring [15–21].

in the cooperative is being simultaneously monitored by all of her peers - is commonly observed [15], other monitoring structures deserve consideration. An interesting departure from the mutual structure is the "*localized monitoring*" in which every farmer monitors (and is monitored) by only one of her peers avoiding therefore the duplication of monitoring. We show that in equilibrium the localized monitoring effort is higher than twice the mutual monitoring level. This result is driven by the distributional character of peer monitoring, where monitoring allows cooperative members to shift the cooperative fine on others in addition to reducing theft.

The paper is organized as follows. In Section 2, we review the relevant literature. Section 3 sketches our model. In Section 4, we present an individual water use-based incentive scheme. In Section 5, we propose two total water use-based incentive schemes. We state a number of propositions describing the dependence of groundwater theft on a number of determinants, some of which are themselves determined by more fundamental factors including costs of monitoring. Section 6 provides two extensions of the basic model: the analysis first allows for collusion in monitoring efforts of cooperative members and then compares different monitoring structures. Section 7 proposes some policy recommendations. In Section 8, we present some potential extensions for further research. Section 9 concludes. Mathematical details are relegated to an Appendix.

2. Literature review

Our research relates to various types of literature emphasizing the team nature of a problem. It relates to the peer monitoring on group lending programs and to decentralized groundwater management literatures, where peer monitoring is recognized as an effective instrument in mitigating the moral hazard behavior of individuals linked by a collective responsibility rule. It also relates to the non-point source pollution and to the non-point groundwater withdrawals, where unobserved individual emissions (withdrawals) can be regulated through instruments based on collective performance, which is the level of observed aggregate (ambient) pollution (withdrawals).

In the peer-monitoring literature, peer monitoring is an important means to mitigate free riding in groups of borrowers related by a joint-liability clause that creates an incentive mechanism in which each group member has an interest in screening and monitoring the other members. In the case of non-repayment by the group, all members will be denied future access to loans from the program, and defaulters who are caught may face fixed social sanctions. The seminal publications in this area are Stiglitz [19] and Varian [21], who show that the (costless) peer monitoring within groups can prevent members' shirking in their productive efforts (Varian), and reduce poor project selection (Stiglitz), improving thereby repayment rates and reducing the costs of lending. More recently several papers including Ghatak and Guinnane [20], Armendariz [15], Che [17], and Conning [18], elaborate on the Stiglitz-Varian models, relax the assumption of the costless peer monitoring and deal with various extensions including the optimal group size, monitoring structures and the dynamic aspect of contractual relationship between group members.

In the context of decentralized groundwater management, Montginoul et al. [22] mentioned the use of a mechanism that consists of providing incentives for all groundwater users getting involved in the monitoring of groundwater abstraction to monitor each other, in order to increase the probability of control. The cost of decentralized monitoring (peer monitoring) is expected to be lower, since agents have more information on the actions of other agents (areas and crops irrigated, irrigation practices and frequencies, etc.) than any centralized structure. The incentive to participate in such a decentralized monitoring system can be provided by redistributing a share of the fine to the person who discovers the defaulter. This system has been used for centuries for regulating access to forests and common pastures in the Italian Alps [23]. This mechanism is likely to be rejected in many cultural contexts as it may be strongly assimilated to denouncement.

The literature on non-point source pollution follows the pioneering work of Segerson [24], whose analysis built on the earlier theoretical analysis of Holmström[6] [14], who addressed the problem of free riding in teams in a more general environment.

Segerson [24] proposed a target based mechanism (TBM) where a regulator should monitor ambient pollution concentrations of a well-defined group imposes to each group member a tax (or a subsidy) proportional to the difference between observed group emission level and the group target. She shows that for a sufficiently high level of the ambient tax, the Nash equilibrium yields an aggregate pollution level equal to the group target.

Segerson's work has inspired several intriguing extensions (e.g., Xepapadeas [25]; Miceli and Segerson [26]; Karp [27]; Millock and Salanié [28]). Xepapadeas [25] proposed a scheme of subsidies and two fining regimes: collective and random fining. Under collective fining, all firms are charged a fine whenever the observed ambient pollution level lies above some predetermined standard. Under the random fining scheme, only one firm is randomly chosen to be punished, irrespective of being responsible for the whole group's deviation from the standard level.

Miceli and Segerson [26] proposed the introduction of collective responsibility rules among group members that create incentives similar to the ones created by ambient taxes. However, Litchenberg [29] noted that these liability rules are not likely to be first-best and are probably best-suited for controlling pollution related to the use of hazardous materials, or for non-frequent occurrences of environmental degradation like oil spills. Karp [27] suggested a model in which polluting firms behave strategically with respect to the regulator and found that their tax burden is lower under an ambient tax than taxes based on individual emissions, provided that the tax adjusts quickly, firms are patient, and the number of firms is small. Millock and Salanié [28] proposed a model of ambient taxes, where polluters might cooperate, and show that ambient taxes give strong incentives towards cooperation. However, when the degree of cooperation is unknown, the optimal regulation requires the regulator to offer a choice between a standard Pigouvian tax and a much lower ambient tax.

Although theoretically appealing, ambient-based schemes are rarely implemented in the field (an exception is presented in Ribaudo, Horan, and Smith [30]) for numerous technical, practical and political reasons [31].

The "ambient tax" instrument proposed by economic literature to solve diffuse pollution problems can be well suited to manage unobserved groundwater withdrawals since withdrawals of a well-defined group can be approximated by the groundwater table level monitored at some observation points [9]. The ambient tax (subsidy) would be charged (paid) to all users if the groundwater table falls below (above) the target level set by a regulator which was decided to not overpass.

In the decentralized management of groundwater several authors including Giordana [32], Lenouvel et al. [12] and Figureau et al. [33], show that contract-based instruments may play a significant role in reducing groundwater over-pumping.

[6] One main finding of Holmström is that in the absence of uncertainty, no budget balancing mechanism exists to solve the problem for avoiding individual free riding in teams.

Giordana [32] proposed three incentive instruments to fight groundwater over-pumping: a tax/subsidy over reported individual withdrawals with a random audit and penalties in case of non-compliance by groundwater users, an ambient tax, and a mixed instrument combing both instruments. He shows that the latter scheme outperforms the former two schemes.

Lenouvel et al. [12] proposed an optional target-based mechanism to reduce groundwater over-exploitation when farmers' behavior is imperfectly monitored. The mechanism combines a classical ambient tax, paid by all farmers of the area when the water table level falls below a pre-defined target, with an optional individual contract signed with the regulator in which signatory farmers commit to provide true information to the regulator concerning the location of their wells, irrigated fields, and volume pumped, and to facilitate the control of this information. These farmers avoid the collective sanction if they comply with an individual quota. This mechanism is tested experimentally in the lab with a contextualized protocol and results show that it reduces withdrawals but that subjects are able to coordinate in a repeated setting to extract an informational rent.

Figureau et al. [33] have proposed three policy instruments, which can be used to enhance farmers' compliance with individual groundwater allocations for irrigation in a decentralized management context. The first policy couples economic incentives by combing the use of a penalty with a reward. The penalty consists of a tax charged to farmers who exceed their allocation and is proportional to the over-pumping. The revenues from this penalty system are then shared between farmers who withdraw less than their entitlement, each one receiving a share proportional to their water saving.

The second policy is a "pooling agreement" through which farmers would agree to mutualize their quotas, in the sense that some farmers agree to relinquish part of their individual water allocation to help other farmers confronted by unusual situations. The volume given back to the Groundwater Users Association (GWUA) is then redistributed to farmers who have an exceptional need for extra water. The internal redistribution follows general principles and rules, which have been validated by the farm community. The contract is favorable to the agents as a team relative to the standard penalty system provided that the team does not exceed the targeted abstraction level, but unfavorable to the team if the target is exceeded. The third policy combines payments and fines. Farmers exceeding their quota pay an increasing block fine for the extra water pumped. Revenues from fines are then redistributed among farmers who use less than their quota; the amount received by farmers is proportional to their water saving efforts.

The three policies are tested through experiments with farmers and results reveal a preference for the third scheme that combines economic and social incentives, as it is expected to meet water and budget balance simultaneously.

Our cooperative model differs from most of the existing theoretical literature on peer monitoring in two respects. First, in their models the punishment is fixed: in the case of non-repayment by the group, all members will be denied future access to loans from the program, and defaulters who are caught may face fixed social sanctions. However, in our model the punishment depends continuously on the extra water pumped by farmers. Second, peer monitoring in this paper is quite specific in that farmers are competing in monitoring, which gives rise to a distributional effect in addition to an incentive effect. Indeed, peer monitoring may allow each cooperative member to shift the cooperative fine on others in addition to mitigating the moral hazard behavior of group members.

As for the ambient tax literature, it differs from the cooperative model in several respects. First, in our model the joint liability clause creates incentives for peer monitoring by group members, while ambient taxes do not. Second, in the ambient tax mechanism each individual is taxed according to the socially marginal damage when ambient emissions deviate from some predetermined level of emission. In our study, however, the distribution of the punishment burden is endogenously determined by peer monitoring. Third, in our study whether efficiency is obtained or not depends on the stringency of the punishment burden. However, most mechanisms suggested in the ambient tax literature are theoretically suitable for implementing the efficient allocation of abatement efforts in a Nash equilibrium.

In the decentralized groundwater management using mechanisms creating incentives for peer monitoring, such incentives are created through joint liability clauses based on rewards rather than punishment sharing rules as in our model.

Our cooperative model differs from decentralized groundwater management using contract-based instruments in three respects. Firstly, their mechanisms do not create incentives for peer monitoring as in our model. Secondly, in our model there are no rewards for farmers using less than the allocated quota. Third, in their models, they mainly use economic instruments as rewards and punishments to mitigate aquifer over-exploitation, but they do not come close to institutional design of the group of groundwater users such as the optimal size of the group and the optimal punishment or reward.

3. The problem

Consider two identical farmers who pump water from a *shared renewable* aquifer to produce a homogeneous farm good. Even in this restricted setting certain features emerge that we believe to be interesting for policy implications and might be relevant for empirical investigations. Suppose that the yield (y) response to water (q) can be described by the relation $y = g(q)$, where $g(.)$ is increasing and concave. Each farmer bears a cost c, measured in units of output for every unit of water used. In addition, the farmer pays a linear price p per unit of water, which is set by the Ministry of Agriculture. The quantity of water maximizing the farmer's profit equates the marginal value product of water to the marginal cost of generating such a quantity

$$q^{fi} : g'(q) = c + p. \tag{1}$$

The superscript ^{fi} refers to the full-information setting. In the complete information setting and when we abstract from any shadow cost of public funds that might imply Ramsey-pricing considerations, the WA can implement the first-best efficient outcome by setting p equal to δ. δ represents the full public cost of mobilizing water to irrigated areas, which includes investment costs, operation and maintenance costs, extraction externalities associated with pumping from a shared aquifer, and any shadow cost associated with the scarcity of water.

The farmer is allocated a *quota* equal to her full-information water use[7], q^{fi}. When the farmer's water use is her private information (unlike the aggregate amount of water used by all farmers which is publicly observable), the farmer who has an individual water meter can well exceed her quota by manipulating her meter. The amount of water used in excess (referred to as goundwater theft) can be written as $\alpha = q - q^{fi}$.

[7] It is hard to understand why the WA as a social planner should ever choose any quota but the full-information water use level.

The response of the WA will differ according to whether there is centralized management or management based on total water use which is publicly and costlessly known. We consider these two cases in turn.

4. Centralized scheme

Here we present the centralized management in an incomplete informational context. In what follows, a few assumptions necessary to the analysis are listed.

- *Assumption 1*: The WA invests in monitoring devices aiming at making individual withdrawals observable. Monitoring incurs a social cost denoted by $\Psi(m)$, which is increasing, convex and satisfies $\Psi(0) = 0$. The cost of monitoring should be understood as including not only measurement devices, but other costs such as the wages of monitors.

- *Assumption 2*: If the farmer is not monitored, then she pays the mandated water fee associated with her allotment, pq^{fi}. Otherwise, she is discovered exceeding her quota (stealing) with a probability $\pi(m)$ which increases with the intensity of monitoring. To simplify the exposition the probability $\pi(.)$ is assumed to be commonly known and takes the form

$$\pi(m) = \min\{\kappa m, 1\}. \tag{2}$$

where $\kappa > 0$ (we assume henceforth that it is sufficiently small to generate an interior solution, which is realistic).

- *Assumption 3*: When the farmer is detected stealing, her individual withdrawal is established without error and she pays pq^{fi} plus a penalty, F^{cs} proportional to the level of theft. The punishment is a monetary transfer from the farmer to the WA and takes the form

$$F^{cs} = f \max\{\alpha, 0\}. \tag{3}$$

where the punishment rate f is positive, greater[8] than p and given outside the model. There are no rewards for using less than the allocated quota. The solutions to the centralized and cooperative managements will be indexed with the superscript ^{cs} and superscript ^{c}, respectively.

- *Assumption 4*: Let $\tilde{Q}$ be the aquifer storage capacity or the stock of the resource in situ. For feasibility requirements we assume throughout that the price of water is lower than the marginal yield of using half of the storage capacity from which is deducted the private cost of one unit of water

$$p \leq g'\left(\frac{\tilde{Q}}{2}\right) - c. \tag{4}$$

[8] Because otherwise the farmer will always have an interest in stealing everything. The net return from theft of water is equal to $(p - \kappa m f)\alpha$, which occurs with the probability $\kappa m < 1$. If $f < p$, one gets $\kappa m f < f < p$, and therefore theft is strictly beneficial; this essentially implies that the net return is maximized when the farmer steals everything.

Rewriting this condition yields $2(g')^{-1}(c+p) \leq \tilde{Q}$ (where $(g')^{-1}(c+p) = q^{fi}$), which states that the total quota allocated to farmers must be lower than the storage capacity. This is to guarantee a rate of utilization that does not exceed the rate of replenishment to avoid the depletion of aquifers.

The order of events is that the WA chooses monitoring[9], m then each farmer chooses the quantity of water to use q^{cs}. In what follows we focus on the subgame perfect equilibrium and solve the model by backward induction. In stage 2 of the game, the farmer chooses q^{cs} so as to maximize her expected payoff:

$$\max_{q} U^{cs}(q; m) = g(q) - cq - pq^{fi} - \kappa m f\left(q - q^{fi}\right).$$

Whose first-order condition is

$$g'(q^{cs}) = c + \kappa m f. \tag{5}$$

The performance of the centralized management relative to the full-information setting depends on the intensity of monitoring as summarized by corollary 1:

COROLLARY 1:

1. *If* $m < \frac{p}{\kappa f}$, *then* $q^{cs} > q^{fi}$;

2. *If* $m \geq \frac{p}{\kappa f}$, *then* $q^{cs} = q^{fi}$.

Where $\frac{p}{\kappa f}$ *is the minimum required level of monitoring that deters theft completely.*

The full-information outcome obtains if the farmer is intensively monitored; Otherwise, theft occurs, as it becomes a privately profitable activity, i.e., the expected net benefit from stealing is $(p - \kappa m f)\left(q^{cs} - q^{fi}\right) > 0$.

Now let us turn to the initial contracting stage, where the WA anticipates the farmer's behavior and picks monitoring, m that maximizes the social welfare function. Specifically this function is the sum of the farmers' surpluses $2\left[g(q^{cs}) - cq^{cs} - pq^{fi} - \kappa m f\left(q^{cs} - q^{fi}\right)\right]$ and the water supplier surplus equal to the revenue from the expected payments for water use, $2\left[pq^{fi} + \kappa m f\left(q^{cs} - q^{fi}\right)\right]$ from which is deducted the cost of mobilizing the resource to the irrigated area, $2\delta q^{cs}$ and the cost incurred by monitoring, $2\Psi(m)$

$$W^{cs}(m, f) = 2[g(q^{cs}) - (c+\delta)q^{cs} - \Psi(m)]. \tag{6}$$

The WA must also consider two major constraints. The first one is the water availability constraint

$$2q^{cs} \leq \tilde{Q}. \tag{7}$$

which reflects the scarcity of the resource: farmers can at most use what is available. And the second one is the replenishment constraint

$$2q^{fi} \leq \tilde{Q}. \tag{8}$$

[9] The WA is able to control the punishment rate, f in addition to controlling the monitoring decision. When punishment is endogenous and costly, some level of punishment is always required in equilibrium. However, because punishment is costly, the optimal response of the WA is to tolerate some theft of water in order to save in punishment costs.

which states that the rate of groundwater utilization should be lower than the replenishment rate. In what follows proposition 1 characterizes the solution to the WA's problem:

PROPOSITION 1: *Suppose that assumptions (1), (2), (3) and (4) hold and constraints (C1) and (C2) bind*[10]*, then the optimal monitoring* m^{cs} *solves*

$$m^{cs} : h\frac{\kappa f}{g''(q^{cs})} = \Psi'(m^{cs}). \tag{9}$$

where μ *is the Lagrangian multiplier on constraint (C1) and* $h = (\kappa m^{cs} f - \delta - \mu)$.

Proof: See the appendix.

The proposition reveals that some monitoring is always required in equilibrium. However, because monitoring is costly, the optimal response of the WA would be to tolerate some theft in order to save in monitoring costs. Moreover, the equilibrium monitoring effort responds directly to the degree of water scarcity, captured by parameter μ (the scarcity rent or shadow value of water).

$$\frac{\partial m^{cs}}{\partial \mu} = \frac{\kappa f}{g''(q^{cs})} \frac{1}{\left[\frac{(\kappa f)^2}{g''(q^{cs})} - h\frac{g'''(q^{cs})}{g''(q^{cs})} - \Psi''(m^{cs})\right]} > 0. \tag{10}$$

The more severe the shortage of water is, the higher is the required monitoring effective at reducing theft.

5. Team-based incentive schemes

5.1 First scheme

We assume that the aggregate water use of the two farmers, $Q = q_1 + q_2$, is publicly and costlessly known, and can be contracted for directly. In particular the WA designs a team-based incentive scheme where it asks the farmer to pay the fixed water fee associated with her allocated quota, pq_i^{fi} and a share of the full extra amount if actual water use exceeds the total quota allocated to the group, $s_i\left[p.\left(Q - 2q_i^{fi}\right)\right]$ for $i = 1, 2$, where $s_i(.)$ is differentiable. We use a very restricted strategy set for the agents, and we shall look only at symmetric equilibria which implies that

$$q_i^{nbb} = q^{nbb} \text{for} i = 1, 2.$$

and that every team member is allocated the same quota $q_i^{fi} = q^{fi}$ for $i = 1, 2$. The solution to this problem is indexed with the superscript ^{nbb}, referring to *non balanced budget*.

The order of events is that taking the price of water[11] p for given, each farmer chooses the quantity of water to use q^{nbb} that maximizes her expected payoff

$$\max_q U(q) = g(q) - cq - pq^{fi} - s_i\left[p.\left(Q - 2q^{fi}\right)\right].$$

[10] Since $q^{cs} \geq q^{fi}$, then (C2) is only binding if (C1) is also binding, and so we can ignore (C2).

[11] Which is set by the Ministry of Agriculture.

Whose first-order condition is

$$g'(q) = c + s_i'\left[p.\left(Q - 2q^{fi}\right)\right].p, \tag{11}$$

A mere comparison of (1) and (11) gives

$$s_i'\left[p.\left(Q - 2q^{fi}\right)\right].p = p,$$

and thereby

$$s_i'\left[p.\left(Q - 2q^{fi}\right)\right] = 1,$$

Implying that each farmer has to pay the total liability, $p.\left(Q - 2q^{fi}\right)$ to the WA.

$$s_i\left[p.\left(Q - 2q^{fi}\right)\right] = p.\left(Q - 2q^{fi}\right). \tag{12}$$

The WA can restore the full-information outcome by administering incentive schemes that *do not balance the budget*[12] since both farmers will be paying the full extra amount $p.\left(Q - 2q^{fi}\right)$.

This incentive scheme works independently of the team size, but its implementation may be constrained by the farmers' limited liabilities. That is why the WA may promote cooperative behavior.

5.2 Cooperative management

Similarly to the previous scheme we assume that the total water use by cooperative members, $Q = q_1 + q_2$, is publicly observable, and aggregate payments from the cooperative to the WA can be conditioned on it. In particular, this feature allows for a collective responsibility rule: when theft occurs, the cooperative as a whole receives a punishment proportional to the total amount of water stolen:

$$F^c = f\left(\sum_{i=1,2} q_i - q_i^{fi}\right). \tag{13}$$

Now suppose that, relative to the WA, farmers have informational advantages in monitoring each other, as a result of social ties and/or spatial proximity and neighborhood and/or long term trade relations.

We assume that peer monitoring brings about only evidence of the occurrence theft but not of its amount.[13] The WA may then contemplate the possibility of inducing peer monitoring between cooperative members by setting a collective responsibility rule that makes all members jointly liable: If theft occurs, the fine inflicted on the cooperative as a whole is shared equally between farmers who are caught stealing; otherwise it is shared by all members.

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[12] If the WA has instead administered the incentive scheme where the total liability $p.\left(Q - 2q^{fi}\right)$ was fully shared among the agents, this would result in an inefficient outcome [14]. The point is therefore not that group punishments is the only effective scheme, but rather budget-breaking is the essential instrument in neutralizing the free-riding problem.

[13] All what a farmer may observe is whether the other cooperative members manipulate their meters and if they do, the evidence about these actions will be established with certainty. Indeed, only the farmer herself and the WA can have access to the farmer's water meter.

Performing peer monitoring is costly, we denote by $\psi(m)$ the associated cost, which is assumed to be increasing, convex and satisfies $\psi'(0) = 0$. Each farmer commits to a level of monitoring[14] (observable by the other members) before the choice of the level of water to use is made. The probability that a farmer i is caught stealing water is then given by:

$$\pi_i(m_j) = \min\{\kappa m_j, 1\}, \tag{14}$$

where $\kappa > 0$. Farmers do not collude in either their production or monitoring decisions.[15]

The order of events is that taking for given the price of water p, cooperative members choose m_i, then having observed each others' choice of m_i they choose the level of water to use q_i. Suppose that both farmers steal water, i.e., $\alpha_k > 0$ for $k = i, j$. The expected share[16] of farmer i from the cooperative fine is decreased by her peer's monitoring, and is in turn increased by her own monitoring.

$$s_i^{\exp} = \frac{1}{2}(1 - \kappa m_i + \kappa m_j). \tag{15}$$

The subgame perfect equilibrium is the profile $(m_1^c, m_2^c, q_1^c, q_2^c)$ of monitoring efforts $m_i^c \geq 0$ and water use levels q_i^c mapping from the set of monitoring decisions into the set of water use decisions, $q_i^c : [0, +\infty)^2 \to 0, \tilde{Q})$. In what follows we shall focus on *symmetric* equilibria which imply that

$$q_i^c = q^c \text{ and } m_i^c = m^c \text{ for } i = 1, 2.$$

and that every cooperative member is allocated the same quota $q_i^{fi} = q^{fi}$ for $i = 1, 2$.

Similarly to the centralized structure, in cooperatives we shall restrict attention to the punishments that are higher than the price of water, i.e., $f > p$, because otherwise farmers will always have an interest in stealing everything. The outcome will depend on the stringency of the punishment rate. If it is sufficiently high, i.e., when f lies above $2p$, farmers will neither steal, nor monitor in equilibrium (as high punishments ensure that the collective penalty will be severe enough to deter theft). Otherwise[17], i.e., when $f \in (p, 2p)$, farmers will steal and monitor in equilibrium. Summarizing:

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[14] One may think of observable sunk investments (such as tools and equipment) being made by members of the cooperative, and which would commit them to a higher monitoring effort. For instance, it is widely observed in developing countries like Tunisia that landlords build small houses in their farms where they can keep some farm equipment for daily use and where both landowners and agricultural laborers may spend some time.

[15] For the moment we sidestep the issue of collusion in monitoring efforts, but we return to it later in Section 7.1.

[16] The expected share of farmer i from the cooperative fine when everyone steals water is given by

$$s_i^{\exp} = \frac{1}{2}\kappa m_i \kappa m_j + \kappa m_j(1 - \kappa m_i) + \frac{1}{2}(1 - \kappa m_i)(1 - \kappa m_j)$$

Where the first term corresponds to her share when both farmers are caught stealing, the second term is her share when she is caught and farmer j not, and the last term is her share when none is caught. Rewriting the expression above yields the expression (15) in the text.

[17] It is worth noting that focusing on this range of punishment levels is less restrictive than it seems. Indeed, such a restriction holds only for the two-farmer cooperative; for the more general case of n-farmer cooperative, punishment rates will instead strictly lie between p and np.

PROPOSITION 2: *If $f \geq 2p$, there exists a unique symmetric subgame perfect equilibrium (q^c, m^c) such that*

$$q^c = q^{fi} \text{ and } m^c = 0. \tag{16}$$

If $p < f < 2p$. Then, the unique symmetric subgame perfect (q^c, m^c) satisfies

$$q^c : g'(q) = c + \frac{1}{2}f, \tag{17}$$

and

$$m^c = \phi(k_2). \tag{18}$$

Where, $k_2 = f\left[\left(q^c - q^{fi}\right) - \frac{1}{4}\frac{f}{g''(q^c)}\right]$ and $\phi = (\psi')^{-1}$.

Proof: See the appendix.

Peer monitoring reduces groundwater theft[18] (*incentive effect*) and it may allow every cooperative member to shift[19] the cooperative fine on the others (*distributional effect*).

The immediate corollary of proposition 2 is that the comparative evaluation of the performance of the two team-based incentive schemes depends on the stringency of punishment rates. For sufficiently stringent punishments (i.e., $f \geq 2p$), the incentive problem is eliminated altogether and the full-information outcome obtains. Otherwise, theft occurs in cooperatives and a positive monitoring effort is required in equilibrium; consequently, the first team-based incentive scheme outperforms the cooperative management. The following corollary states this point.

COROLLARY 2:

1. *If $f \geq 2p$, then*

$$q^c = q^{nbb} \text{ and } W^c = W^{nbb}, \tag{19}$$

2. *If $p < f < 2p$, then*

$$q^c > q^{nbb} \text{ and } W^c < W^{nbb}. \tag{20}$$

Where, $q^{nbb} = q^{fi}$ and $W^c = 2[g(q^c) - (c+\delta)q^c - \psi(m^c)]$ and $W^{nbb} = W^{fi} = 2\left[g\left(q^{fi}\right) - (c+\delta)q^{fi}\right]$ are the cooperative and full-information social welfare levels, respectively.

5.3 Comparative statics

To obtain explicit solutions where possible we assume that monitoring costs take the quadratic form $\psi(m) = \frac{1}{2}bm^2$ where $b > 0$. We first investigate the impact of

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[18] The partial derivative of the level of theft undertaken by farmer i with respect to monitoring performed by her peer, m_j is given by

$$\frac{\partial\left(q_i - q^{fi}\right)}{\partial m_j} = \frac{\kappa f}{2g''(q_i)} < 0.$$

[19] This finding follows from equation (15). The expected share of farmer i from the total fine increases with the monitoring effort performed by her peer, m_j:

$$\frac{\partial s_i^{\exp}}{\partial m_j} = \frac{1}{2}\kappa > 0.$$

water price and punishment on the equilibrium level of theft. As one intuitively expects, theft increases with water price and decreases with punishments:

$$\frac{\partial\left(q^c - q^{fi}\right)}{\partial f} = \frac{\partial q^c}{\partial f} = \frac{1}{2g''(q^c)} < 0. \tag{21}$$

$$\frac{\partial\left(q^c - q^{fi}\right)}{\partial t} = -\frac{1}{g''(q^c)} > 0. \tag{22}$$

We now show how the intensity of monitoring will be related to monitoring costs, punishments and the price of water. Monitoring is decreasing with the costs of monitoring and increasing with water price and punishment.[20]

$$\frac{\partial m^c}{\partial b} = -\frac{k_2}{b^2} < 0. \tag{23}$$

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[20] From equation (B4) in the proof of proposition 2 in the appendix, we have

$$\psi'(m_i) = \left\{ \begin{array}{c} \frac{1}{2}\kappa f\left[\left(q_i - q^{fi}\right) + \left(q_j - q^{fi}\right)\right] \\ -\frac{1}{2}f(1 - \kappa m_i + \kappa m_j)\frac{\partial\left(q_j - q^{fi}\right)}{\partial m_i} \end{array} \right\},$$

The partial derivative of $\psi'(m_i)$ with respect to m_i gives

$$\psi''(m_i) = \left\{ \begin{array}{c} \frac{1}{2}\kappa f\left[\frac{\partial}{\partial m_i}\left(q_i - q^{fi}\right) + \frac{\partial}{\partial m_i}\left(q_j - q^{fi}\right)\right] \\ -\frac{1}{2}f(-\kappa)\frac{\partial\left(q_j - q^{fi}\right)}{\partial m_i} - \frac{1}{2}f(1 - \kappa m_i + \kappa m_j)\frac{\partial^2\left(q_j - q^{f_i}\right)}{\partial m_i^2} \end{array} \right\},$$

$$\text{Where, } \left\{ \begin{array}{c} \frac{\partial\left(q_i - q^{fi}\right)}{\partial m_i} = -\frac{\kappa f}{2g''(q_i)}; \\ \frac{\partial\left(q_j - q^{fi}\right)}{\partial m_i} = \frac{\kappa f}{2g''\left(q_j\right)}; \\ \text{and} \\ \frac{\partial^2\left(q_j - q^{fi}\right)}{\partial m_i^2} = \frac{(\kappa f)^2}{4}\left(-\frac{g'''\left(q_j\right)}{\left[g''\left(q_j\right)\right]^3}\right). \end{array} \right.$$

Replacing the above derivatives by their expressions into the expression of $\psi''(m_i)$ and taking into account that the symmetric equilibrium involves that $m_i = m_j = m^c$ and $q_i = q_j = q^c$, yields

$$\psi''(m_i) = \frac{(\kappa f)^2}{4g''(q^c)}\left[1 + \frac{f}{2}\frac{g'''(q^c)}{[g''(q^c)]^2}\right],$$

Given that the cost of monitoring is an increasing and convex function ($\psi''(m_i) > 0$) and $g''(q^c) < 0$, then one gets

$$\left[1 + \frac{f}{2}\frac{g'''(q^c)}{[g''(q^c)]^2}\right] < 0,$$

which implies that $g'''(q^c) < 0$:

$$g'''(q^c) < -\frac{2}{f}[g''(q^c)]^2 < 0$$

And hence the partial derivative of monitoring with respect to the punishment rate is positive:

$$\frac{\partial m^c}{\partial f} = \frac{1}{b}\left[\left(q^c - q^{fi}\right) + \frac{f^2}{8}\frac{g'''(q^c)}{[g''(q^c)]^3}\right] > 0.$$

$$\frac{\partial m^c}{\partial p} = \phi'(k_2)\left(\frac{-f}{g''(q^c)}\right) > 0. \tag{24}$$

$$\frac{\partial m^c}{\partial f} = \frac{1}{b}\left[\left(q^c - q^{fi}\right) + \frac{f^2}{8}\frac{g'''(q^c)}{\left[g''(q^c)\right]^3}\right] > 0. \tag{25}$$

A higher water price increases the incentives for theft and the punishment burden that would be incurred by a member who was the only one to be caught, inducing farmers to perform more monitoring to shift the cooperative fine on the others.

In the range of non stringent punishments, there is a higher scope for theft, and an increase in the punishment rate renders the punishment burden for a given level of theft high, and also the total punishment that would be incurred by a member who was the only one to be caught. This would increase the farmers' incentives to compete more in monitoring to shift the cooperative fine on the others. The results above suggest that the distributional effect of peer monitoring is very likely to always dominate the incentive effect.

It is interesting to compare the equilibrium monitoring effort to the socially optimal one. We compare equilibrium outcomes to those that would occur in a second-best problem faced by the WA as a social planner who can decide about monitoring levels of farmers but not their water use choices once monitoring decisions have been made. In addition, we assume that the WA cannot affect the farmers' incentives to steal water for given monitoring levels. In particular, the WA cannot ensure that farmers do not steal the resource. The WA chooses a monitoring level, m^* which maximizes the social welfare function

$$\max_{m\geq 0} 2\left[g(q^c) - (c+\delta)q^c - \psi(m)\right]. \tag{26}$$

It is socially optimal not to monitor in cooperatives governed by these rules ($m^* = 0$) whenever monitoring is costly. Farmers over-monitor in equilibrium, $m^c > m^*$, because of their *rent seeking* behavior which results from the dominance of the distributional effect of peer monitoring over the incentive effect.

5.4 Endogenous punishment

Here the basic analysis is extended to allow for endogenous punishment, where the punishment rate f is collectively chosen by cooperative members at an initial contracting stage. Inflicting punishment f is costly, we denote by $\varphi(f)$ the associated cost that can be either pecuniary or manifest in nature when there is deterioration of social relations from inflicting punishment on members of a close-knit society. $\varphi(f)$ is increasing and strongly convex (i.e., $\varphi'''(f) > 0$ in addition to $\varphi''(f) > 0$), and satisfies $\varphi(0) = 0$. The strong convexity of φ is driven by the increased complexity and difficulty of enforcing more and more stringent punishments on relatives, neighbors and friends.

Cooperative members choose the punishment rate f^c that maximizes an objective function defined as the sum of the cooperative members surpluses, $2\left[g(q^c) - cq^c - pq^{fi} - f\alpha^c - \frac{1}{2}b(m^c)^2\right] - \varphi(f)$ and the WA's surplus, which is equal to its revenue from water proceeds, $2pq^{fi}$ from which is deducted the cost of proving water to the cooperative area, $2\delta q^c$.

$$\max_{f} W^c(f) = 2\left[g(q^c) - (c+\delta)q^c - f\alpha^c - \frac{1}{2}b(m^c)^2\right] - \varphi(f). \tag{27}$$

This has a first-order condition[21]:

$$f^c : -\frac{1}{g''(q^c)}\left(\gamma + \frac{1}{2}f\right) - 2\left(q^c - q^{fi}\right) - 2\frac{k_2}{b}\left\{\left[\left(q^c - q^{fi}\right) + \frac{f^2}{8}\frac{g'''(q^c)}{\left[g''(q^c)\right]^3}\right]\right\} = \varphi'(f) \tag{28}$$

which is also sufficient[22] to identify a global maximum.

From this condition one can show that the punishment level is decreasing with monitoring costs. Totally differentiating the first order condition with respect to f and b and rearranging yields:

$$\frac{\partial f^c}{\partial b} = \frac{2k_2}{Gb^2}\left\{\left[\left(q^c - q^{fi}\right) + \frac{f^2}{8}\frac{g'''(q^c)}{\left[g''(q^c)\right]^3}\right]\right\} < 0. \tag{29}$$

where[23] $G = \frac{d^2W^c}{df^2} < 0$. This result confirms that the two instruments, monitoring and punishment *complement* each other, as an increase in the cost of one reduces the level of the other.

6. Cooperative size

The analysis thus far has remained restricted to the two-farmer cooperative. However, in practice, most cooperatives irrigating from aquifers involve up to as many as 40 farmers, and most cooperatives using surface water involve more than 100 farmers [20]. We investigate here the optimal cooperative size, where the basic set-up is extended from the two-farmer cooperative to the n-farmer one.[24]

We characterize the symmetric subgame perfect equilibrium $\left(q_n^c, m_n^c\right)$ for the relevant range of non stringent punishments, $p < f < np$ (assuming that the second-order condition for a maximum holds[25]):

$$q_n^c : g'(q) = c + \frac{1}{n}f, \tag{30}$$

[21] Differentiating the cooperative welfare function with respect to f yields

$$\frac{dW^c}{df} = 2\left\{\left[g'(q^c) - (c+\delta)\right]\frac{\partial q^c}{\partial f} - \alpha^c - f\frac{\partial \alpha^c}{\partial f} - 2\frac{1}{2}bm^c\frac{\partial m^c}{\partial f}\right\} - \varphi'(f) = 0.$$

Taking into account that q^{fi} does not depend on f, we then have $\frac{\partial \alpha^c}{\partial f} = \frac{\partial q^c}{\partial f} = \frac{1}{2g''(q^c)}$. Replacing $\frac{\partial \alpha^c}{\partial f}$ and $\frac{\partial m^c}{\partial f}$ by their expressions given respectively by equations (21) and (25) in the above expression, yields the first-order condition given by equation (28) in the text.

[22] This follows from the strong convexity of the cost of inflicting punishment on cooperative members, ensuring therefore the concavity of the objective function $W^c(f)$.

[23] The negative sign of the second-order derivative follows from the concavity of function W^c.

[24] Unlike the two-farmer case where peer monitoring is necessarily mutual, the n-farmer case opens the scope for various kinds of monitoring structures. We will however, momentarily focus on the "mutual monitoring" structure, whereby each farmer monitors all her peers.

[25] It is quite difficult to derive the second-order condition for this problem because the first-order conditions account for the following highly complicated term

$$\phi_n(\kappa m) = (1-\kappa m)^{(n-2)}\sum_{k=1}^{n-1}(1-\kappa m)^{(n-1)(k-1)}.$$

$$m_n^c : k_n \Phi_n(\kappa m) = (n-1)\psi'[(n-1)m]. \tag{31}$$

Where

$$\begin{cases} k_n = f\left[\left(q_n^c - q^{fi}\right) - \dfrac{1}{n^2}\dfrac{f}{g''\left(q_n^c\right)}\right] > 0 \\ \text{and} \\ \Phi_n(\kappa m) = \left\{(1-\kappa m)^{(n-2)(n-1)}\sum_{k=1}^{n-1}(1-\kappa m)^{(k-1)}\right\} \\ = \left\{\dfrac{1}{\kappa m}(1-\kappa m)^{(n-2)(n-1)}\left[1-(1-\kappa m)^{n-1}\right]\right\} \end{cases}.$$

From the necessary conditions one can see that the farmer withdraws more water as the cooperative becomes larger:

$$\frac{\partial q_n^c}{\partial n} = -\frac{1}{n^2}\frac{f}{g''\left(q_n^c\right)} > 0. \tag{32}$$

meaning that larger groups increase the incentives for theft. However, it is not clear whether the equilibrium monitoring level tends to increase or decrease with the cooperative size. The intuition suggests that the group size affects the incentive problem in two ways. A larger group discourages monitoring, as the evidence about the farmer's theft could be established when she is detected stealing by at least one of her peers. Monitoring all together might hence become useless, as the same outcome could be achieved with a smaller number of farmers, avoiding thereby the useless duplication of monitoring. This free-riding problem reduces the farmers' incentives for monitoring. On the other hand, a larger group may increase the total amount of water stolen in the cooperative, increasing therefore the maximum punishment that would be incurred by a member who was the only one to be caught. This would rather increase the farmer's incentives to monitor more intensively to catch the other members stealing, which may reduce her expected share from the total fine. This *rent-increasing effect* will thus counteract the above *free-riding effect* by encouraging more intense monitoring as the cooperative becomes larger.

It is very difficult to derive an analytical expression of monitoring level in equilibrium, as monitoring is implicitly given by (31). In order to get some insights, we will proceed in the remainder of this section to the following simplification: we restrict attention to sufficiently small values of κ, which implies that all terms in κ^n for $n \geq 2$, become of the second-order and can thereby be dropped from our calculations. Consequently (31) reduces to[26]

$$m_n^c : (n-1)[\psi'(n-1)m] \simeq k_n(n-1)[1-(n-1)(n-2)\kappa m]. \tag{33}$$

To obtain explicit solutions where possible we assume that monitoring costs take the quadratic form $\psi(m) = \frac{1}{2}bm^2$ where $b > 0$. Rewriting (33) yields the approximated equilibrium monitoring effort

$$m_n^c \simeq \frac{k_n}{(n-1)[b + k_n\kappa(n-2)]}, \tag{34}$$

[26] This simplification involves no major loss of insights, as equation (33) captures the main qualitative aspects of the solution to the cooperative model.

Monitoring decreases with monitoring costs which is straightforward

$$\frac{\partial m_n^c}{\partial b} = -\frac{k_n}{(n-1)[b + k_n\kappa(n-2)]^2} < 0, \tag{35}$$

As for the impact of the cooperative size on monitoring it is given by

$$\frac{\partial m_n^c}{\partial n} \simeq \theta \frac{\partial k_n}{\partial n}, \tag{36}$$

Where $\theta = \frac{b}{(n-1)[b+k_n\kappa(n-2)]^2} > 0$, which means that the signs of the two partial derivatives $\frac{\partial m_n^c}{\partial n}$ and $\frac{\partial k_n}{\partial n}$ are the same. $\frac{\partial k_n}{\partial n}$ is equal to

$$\frac{\partial k_n}{\partial n} = f\left\{\left(1 + \frac{g'''(q_n^c)}{n^2[g''(q_n^c)]^2}\right)\frac{\partial q_n^c}{\partial n} + \frac{2f}{ng''(q_n^c)}\right\}, \tag{37}$$

Plugging the expression of $\frac{\partial q_n^c}{\partial n}\partial n$ given by (32) into (37) yields

$$\frac{\partial k_n}{\partial n} = \frac{f^2}{ng''(q_n^c)}\left\{\left(2 - \frac{1}{n}\right) - \frac{g'''(q^c)}{n^3[g''(q_n^c)]^2}\right\}. \tag{38}$$

which sign is ambiguous because the term in the bracket parenthesis has an ambiguous sign (the terms $\left(2 - \frac{1}{n}\right)$ and $\frac{g^{(3)}(q^c)}{n^3[g''(q_n^c)]^2}$ are both strictly positive and it is not clear which term overcomes the other). Because of the analytical complexity of the problem, we will address this issue via a numerical example - the example is:

- The production function is $g(q) = \sqrt{q}$;
- The per-unit private cost and price of water are $c = p = 0.2$;
- The transaction costs related to monitoring take two different values $b = 3$ and $b = 10$.

Simulations suggest that the shape and the value of monitoring, $m^c(n)$ as a function of the cooperative size considerably changes when monitoring costs vary. When $b = 3$, the monitoring function gradually decreases as the cooperative becomes larger, i. e., for $n \geq 3$. This means that the *free riding* effect tends to always dominate for small monitoring costs. Whereas, for $b = 10$, monitoring levels become smaller and, the function increases for small values of n and starting from $n = 4$ it gradually declines. This implies that for large monitoring costs the *rent seeking* effect might come into play. Simulation results suggest the existence of a monitoring cost, $\overline{b}$ such that:

- For any $b < \overline{b}$, the equilibrium monitoring $m^c(n)$ is decreasing with the cooperative size and;
- For any $b > \overline{b}$, the equilibrium monitoring $m^c(n)$ increases up to some level $\tilde{n}$ and then gradually declines.

We now explore the optimal cooperative size. Farmers may seek a group size $n_{\max}$ that maximizes the *average*[27] cooperative welfare function $W_A^c(n)$

$$n_{\max} \in \arg\max_{n \geq 2} W_A^c(n) = g(q_n^c) - (c+\delta)q_n^c - \psi(m) \tag{39}$$

The first-order condition for an interior solution (assuming that the second-order condition holds) is given by:

$$\left[g'(q_n^c) - (c+\delta)\right]\left(\frac{\partial q^{c_n}}{\partial n}\right) - \psi'(m_n^c)\left(\frac{\partial m_n^c}{\partial n}\right) = 0, \tag{40}$$

The (first-order) change in social welfare attributable to a marginal entrant is composed of two terms. The first term implies that the new entrant causes every member to better free ride on her peers and thus to contract her monitoring effort. This would increase the opportunities for theft for everyone. This *stealing* effect causes a reduction in social welfare of

$$\left[g'(q_n^c) - (c+\delta)\right]\left(\frac{\partial q_n^c}{\partial n}\right) < 0, \tag{41}$$

On the positive side, free riding results in monitoring cost savings. This *cost savings* effect brings about an increase in social welfare of

$$-\psi'(m_n^c)\left(\frac{\partial m_n^c}{\partial n}\right) > 0. \tag{42}$$

The optimal cooperative size, $n_{\max}$ equates the social marginal benefit stemming from monitoring cost savings to the social marginal losses caused by a higher occurrence of theft. The net benefits of peer monitoring are maximized when the cooperative size is neither too small (due to the "*monitoring cost savings*" effect) nor too large (due to the "*stealing*" effect).

The effect of the group size on the cooperative welfare is found to be analytically complicated, that is why we use a numerical example to shed light on the intensity of *stealing* and *cost savings* effects when one varies monitoring costs. Simulations are performed for the same production function and the same parameter-values considered above, to which we add the value of the external cost of water $\delta = 3$. Simulation results suggest that for $b = 3$, the welfare function is maximized for $n_{\max} = 4$, while in the other case it is gradually decreasing. This means that the *stealing* effect dominates almost everywhere and the best policy of the WA is to implement small and medium cooperatives.

Finally, simulations suggest that monitoring costs reduce the cooperative size. The intuition is that higher monitoring costs make it more difficult to monitor, which gives more opportunities for theft, requiring smaller cooperatives to compensate.

7. Extensions

7.1 Collusion

The cooperative model described up until now corresponds to a non-cooperative game. Each cooperative member is out to maximize her expected payoff, and makes

[27] The rational for the choice of the average social welfare function rather than the absolute one is that for the latter the group size effect might always dominate and the function is very likely to always increase with the cooperative size.

her decisions about monitoring and water use independently of the other members. What happens if we relax this assumption and consider possibilities of coordinated actions about monitoring? A natural model is to consider what happens if the two cooperative members choose their monitoring efforts in order to maximize joint payoffs, $\left[U_i(q_i, m_i) + U_j\left(q_j, m_j\right)\right]$. The collusive outcome is given by corollary 3:

COROLLARY 3: *The collusive monitoring efforts are*

$$m_i = m_j = 0. \tag{43}$$

Proof: See the appendix.

The collusive monitoring effort is efficient. In the absence of collusion, cooperative members compete on monitoring because of their *rent-seeking* behavior, though monitoring is useless, as they will always split equally the cooperative fine between themselves.[28] Collusion is thus welfare enhancing, as it yields the same outcome and saves in monitoring costs.

7.2 Monitoring structures

Although in practice the mutual monitoring structure - whereby each farmer in the group is being simultaneously monitored by all of her peers - is commonly observed [15], other monitoring structures deserve consideration. An interesting departure from the mutual structure is the "*localized monitoring*" in which every farmer monitors (and is monitored) by only one of her closest neighbors, say each farmer monitors her left neighbor and is monitored by her right neighbor. There is a natural argument in favor of monitoring structures of the latter kind: it can potentially avoid duplication[29] of monitoring. As a first and very tentative attempt to explore the issue of the optimal design of peer monitoring structures, we shall compare the mutual monitoring (MM) to the localized monitoring (LM) one with regard to the equilibrium water use and monitoring levels and thereby to the cooperative welfare level. The comparison will be held for a three-farmer cooperative.

7.2.1 Mutual monitoring

Consider a cooperative formed by three farmers i, j and k applying *mutual peer monitoring.* We assume that a farmer monitors each of her peers with the same monitoring effort, which means that the cost of monitoring all others members is equal to $\psi(2m_l)$ for $l = i, j, k$..

The subgame perfect equilibrium is the profile $\left(m_l^{c(MM)}, q_l^{c(MM)}\right)_{l=i,j,k}$ of monitoring efforts $m_l^{c(MM)} \geq 0$ and water use levels, $q_l^{c(MM)}$ mapping from the set of monitoring decisions into the set of water use decisions, $q_l^{c(MM)} : [0, +\infty)^3 \to 0, \tilde{Q})$

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[28] This finding comes from the symmetric equilibrium which implies that cooperative members perform the same level of monitoring, i.e., $m_i^c = m_j^c = m^c$. It follows that the expected share of farmer i from the total fine is equal to $\frac{1}{2}$:

$$\begin{aligned} s_i^{\exp} &= \frac{1}{2}\left(1 - \kappa m_i^c + \kappa m_j^c\right) = \frac{1}{2}(1 - \kappa m^c + \kappa m^c) \\ &= \frac{1}{2} \end{aligned}$$

[29] Duplication in the mutual structure obviously takes place when the number of farmers in the cooperative is larger than two.

(where the superscript $^{c(MM)}$ refers to cooperatives characterized by mutual monitoring). In what follows we shall focus on *symmetric* equilibria which imply that

$$q_l^{c(MM)} = q_3^{c(MM)} \text{and} m_l^{c(MM)} = m_3^{c(MM)} \text{for } l = i, j, k.$$

(assuming that the second-order condition for a maximum holds). The solution to this problem is summarized in proposition 3:

PROPOSITION 3: *If $p < f < 3p$, there exists a unique symmetric subgame perfect equilibrium $\left(m_3^{c(MM)}, q_3^{c(MM)}\right)$ satisfying*

$$q_3^{c(MM)} : g'(q) = c + \frac{1}{3} f, \tag{44}$$

and

$$m_3^{c(MM)} : \left\{ \begin{array}{c} -\dfrac{f^2}{9g''\left(q_3^{c(MM)}\right)} \left[\begin{array}{c} \kappa^4 m^4 + \frac{1}{2}\kappa^4 m^3 \\ -2\kappa^3 m^3 - \frac{5}{2}\kappa^3 m^2 \\ +3\kappa^3 m \end{array} \right] \\ -f\left(q_3^{c(MM)} - q^{fi}\right) \left[\begin{array}{c} \kappa^4 m^3 - 3\kappa^3 m^2 \\ +4\kappa^2 m - 2\kappa \end{array} \right] \end{array} \right\} = 2\psi'(2m). \tag{45}$$

Proof: See the appendix.

7.2.2 Localized monitoring

By the same token, consider a three-farmer cooperative in which farmers i, j and k apply *localized monitoring* whereby each farmer monitors her left neighbor and is monitored by her right neighbor. We assume that farmer i monitors farmer j with the monitoring level $m_{ij} = m_i$, and farmer j monitors farmer k with the monitoring effort $m_{jk} = m_j$, and farmer k monitors farmer i with the monitoring effort $m_{ki} = m_k$. We characterize the symmetric subgame perfect equilibrium (the superscript $^{c(LM)}$ refers to cooperatives characterized by localized monitoring)

$$q_l^{c(LM)} = q_3^{c(LM)} \text{ and } m_i^{c(LM)} = m_3^{c(LM)} \text{for} l = i, j, k.$$

(assuming that the second-order condition for a maximum holds). The solution to this problem is characterized by proposition 4:

PROPOSITION 4: *If $p < f < 3p$, there exists a unique symmetric subgame perfect equilibrium $\left(m_3^{c(LM)}, q_3^{c(LM)}\right)$ which satisfies*

$$q_3^{c(LM)} : g'(q) = c + \frac{1}{3} f, \tag{46}$$

and

$$m_3^{c(LM)} : \left(-\frac{1}{2}\kappa^2 m + \kappa\right) \left[\begin{array}{c} -\dfrac{f^2}{9g''\left(q_3^{c(CI)}\right)} \\ +f\left(q_3^{c(CI)} - q^{fi}\right) \end{array} \right] = \psi'(m). \tag{47}$$

Proof: See the appendix.

Comparing the monitoring levels in both settings is not straightforward, however under certain relevant circumstances one can say something. For sufficiently small κ, the terms κ^n for $n \geq 2$, become of the second-order and equations (45) and (47) above reduce respectively to

$$\kappa f\left(q_3^{c(MM)} - q^{fi}\right) \simeq \psi'\left(2m_3^{c(MM)}\right). \tag{48}$$

and

$$\left[-\frac{\kappa f^2}{9g''\left(q_3^{c(LM)}\right)} + \kappa f\left(q_3^{c(LM)} - q^{fi}\right)\right] \simeq \psi'\left(m_3^{c(LM)}\right). \tag{49}$$

A mere comparison of (48) and (49) suggests that the equilibrium localized monitoring is higher than twice the equilibrium mutual monitoring

$$m_3^{c(LM)} > 2m_3^{c(MM)}. \tag{50}$$

This result may sound unlikely, one indeed expects farmers to monitor less in cooperatives characterized by localized monitoring, as this structure avoids the duplication of monitoring. But, the rationale for this result comes from the distributional character of monitoring, as cooperative members compete on monitoring to shift the cooperative fine on the others. In the mutual structure, a farmer may well reduce her expected share from the total fine as the cooperative fine might be shared with more than one member. However, in the localized structure, each farmer monitors only one of her neighbors increasing the risk to bear the whole punishment burden on her own. This acts as an incentive to monitor more to increase the probability of shifting the fine on that neighbor.

An immediate implication of (44), (46) and (50) is that cooperatives using mutual monitoring welfare dominate those using localized monitoring

$$W^{c(MU)}(3) > W^{c(CI)}(3). \tag{51}$$

Where $W^{c(MU)}(3)$ and $W^{c(CI)}(3)$ are welfare levels in the three-farmer cooperatives characterized by mutual and localized monitoring structures, respectively.

8. Policy implications

Surface water is not only scarce but also highly uncertain and often of bad quality in particular in arid and semi-arid regions. Groundwater is seen as a unique guarantee (whenever it is well managed) for the long term viability of an agriculture sector crucial for giving those fragile countries a minimum food security.

The principal aim of this research was to design the appropriate institutions and incentives to reduce groundwater over-exploitation. We have proposed various incentive schemes, some based on individual water use and others on aggregate water use. The model has in particular shown that total water use-based incentive schemes may well overcome the individual water use-based scheme (centralized management). Moreover, the comparative evaluation of the two team-based incentive schemes has shown that for a relevant range of non stringent punishments, the first scheme dominates the cooperative management since it restores the full-information outcome. Nevertheless such a scheme may suffer from a strong implementation problem: endowment constraints may render it infeasible. How to overcome this drawback? The solution could be imported from the theory of "*positive*" assortative matching, where farmers could be sorted into various homogenous groups giving the scope to policy makers to choose the team-based scheme to implement for each group. To illustrate this idea, suppose that the WA could sort farmers into two groups, a group of wealthy farmers and a group of all other farmers. How to screen wealthy farmers from others? Wealthy farmers may well be those who invest more in sophisticated agricultural machinery and/or grow high value crops and/or cultivate large plots of land,...etc. For the group of wealthy farmers, the optimal policy of the WA would be to implement the first team-based scheme; And for the other group, participatory management could be implemented through the creation of a collective responsibility rule that induces peer monitoring by members as modeled above.

Simulations in our paper suggested that the cooperative size is weakly decreasing with monitoring, meaning that the best policy of the WA would be to implement non large cooperatives which would reduce the scope for groundwater overexploitation.

9. Potential extensions for further research

This research could be extended along the following directions. Firstly, we know from simulation results that it is socially beneficial to form small and medium cooperatives. But, what about irrigated areas with a large number of farmers? In practice, centralized structures are in charge of running such areas. In addition, a direct management transfer of these areas to cooperative institutions is unlikely to enhance water use efficiency, as the "*stealing effect*" a major source of inefficiency always dominate in large cooperatives. The cooperative management could however be implemented in a slightly different way through the creation of two hierarchies of cooperatives, *primary* and *secondary* cooperatives. Farmers can form several groups of medium and/or small sizes depending upon whether peer monitoring involves low or high costs. These groups would constitute *secondary cooperatives* where each is run by a number of its members, called "cooperative manager". The secondary cooperatives' managers themselves would form what we call a "*primary cooperative*" playing the role of intermediary between secondary cooperatives and the WA. Among each secondary cooperative's managers, some farmers would be chosen to form the primary cooperative's managers and would be in charge of running it. Every cooperative is governed by similar rules as modeled above: members of the same group are related by some collective responsibility rule which would create incentives for two types of peer monitoring, (a.) *peer monitoring-within* applied within each secondary cooperative and (b.) *peer monitoring-between* applied between secondary cooperatives.

Secondly, in our theoretical study we have formalized the cooperative management where members interact only once, however in practice members interact repeatedly. The knowledge that pursuit of their short-term interests can harm their long-term aims by affecting the reaction of others in the future interactions may be a powerful inducement to behavior that displays apparent solidarity with the interests of the group. When cooperative members are homogenous, in particular they are all landlords and moreover the agricultural activity is their main source of income, their interactions can be modeled as an infinitely repeated game.[30] What one can learn from group lending literature is that such cooperatives might not need to have access to an exogenous penalty device since peer sanctions can be accomplished in the dynamic framework and they are self enforcing [31] [17]. It suffices to make the group members jointly liable for the payment of their total amount of water use, e.g., denying them future access to the public source of water supply or rising the price of water for next periods when theft occurs in the current period. In such a management design, a group member can be penalized by other members' shirking (=stealing), in that a member's shirking increases the payment burden of her peers, and thereby negatively affecting their payoffs. In turn, when cooperative members are heterogenous in that some members are landlords and others are rental contract holders and/or tenants, an exogenous penalty technology might be required, e.g., one may think for example of the exclusion of defaulting users from the cooperative or from the community or from certain kinds of input supply facilities.[32] Whereas, being excluded from the cooperative could be perceived as extremely harmful for a land owner, this might not be the case for rental contract holders who interact only for a finite number of periods and the pursuit of their short-term interests induce them to adopt the strategy of "take the money and run away.[33]" However, this may well harm their long-term interests - the loss of reputation may be very costly for these farmers: their exclusion from the cooperative might make it difficult for them to integrate other cooperatives in the same area and/or even in other areas. In short they might be excluded from the community. What might be critical here is the enforcement of such social sanctions in practice, especially how and why a farmer should ever impose a sanction on a "friend" or "relative" who has defaulted. One possible explanation on the face of it is the impossibility to keep the information about strategic defaults secret. An other explanation may be the harmful consequences of foregoing the punishment of defaulters, e.g., the absence of alternative sources of water supply if the cooperative is denied future access to her principal source of water supply.

10. Conclusion

This paper has investigated the design of the appropriate institutions and rules to enhance groundwater use efficiency by reducing over-pumping of aquifers. We have proposed various incentive schemes, some based on individual withdrawals which are the farmers' private information and some based on the total water withdrawn by

[30] Actually, landlords interact for a finite number of periods but, there is enough uncertainty about the end of their interactions that this can be modeled as an infinite repeated game.

[31] Yeon-Koo Che [17] builds a group lending model where the incentive problem stems from the entrepreneurs' unobservable effort decisions and their liquidity constraints. He shows that when the group members operate their projects repeatedly, the joint liability feature itself makes it credible for members to penalize others through their effort decisions. Under group lending, a member's shirking in her productive effort increases the payment burden of her peers, i.e., a group member can be penalized by other members' shirking.

[32] Armendariz De Aghion [15] reports that social sanctions are observed in practice. For example, in agricultural cooperatives, social sanctions often involve the exclusion of defaulters from privileged access to input supplies and marketing facilities.

[33] At the end of her contract, a rental contract holder may well benefit from water theft without incurring the cost of stealing because she can refuse to pay the punishment since she would leave the cooperative anyway.

all farmers which is publicly observable. In the latter setting, two schemes are proposed. In the first scheme, the WA administers an incentive scheme that does not balance the budget, restoring thereby the full-information water use level. Such scheme works independently of the group size, but it may be infeasible when farmers have endowment constraints. This is why the WA resorts to a second total water use-based incentive scheme by promoting the cooperative behavior. We device cooperative institutions characterized by a joint liability clause that induces peer monitoring by members. We show that higher monitoring costs and larger cooperatives entail more theft and higher punishment levels reduce it. We also show how the cooperative membership and punishments are determined endogenously by constraints on monitoring. Higher monitoring costs increase punishment levels and reduce the size of the cooperative. The basic analysis is then extended to allow first for collusion in monitoring between cooperative members, and show that the collusive monitoring effort is efficient. Secondly, we explore a different monitoring structure "localized monitoring" and compared it with the mutual monitoring structure which is commonly observed in practice. Finally, we use the theoretical results to derive some useful policy recommendations that could help decision makers to implement the right policies to alleviate groundwater over-exploitation.

Overall, these results provide strong confirmation of the ability of well designed incentives and institutions to reduce groundwater over-exploitation, and that constraints on monitoring costs affect institutional design.

Appendix

The details of mathematical demonstrations are available from the authors upon request.

Classification

JEL classification: Q13; Q15; Q25; R48

Author details

Wided Mattoussi[1]*, Mohamed Salah Matoussi[2] and Foued Mattoussi[3]

1 Ecole Supérieure des Sciences Economiques et Commerciales de Tunis (University of Tunis) and Laboratoire de Recherche en Economie Quantitative du Développement (LAREQUAD), Tunis, Tunisia

2 Faculté des Sciences Economiques et de Gestion de Tunis (University of Tunis El Manar) and Laboratoire de Recherche en Economie Quantitative du Développement (LAREQUAD), Tunis, Tunisia

3 Faculté des Sciences Juridiques, Economiques et de Gestion de Jendouba (University of Jendouba) and Laboratoire de Recherche en Economie Quantitative du Développement (LAREQUAD), Jendouba, Tunisia

*Address all correspondence to: wided.mattousse@gmail.com

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