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Exogenous regulatory institutions for sustainable common pool resource management: Application to groundwater

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ABSTRACT

This paper focuses on introducing and comparing various types of external regulatory institutions for management of common pool resources (CPRs), namely the quota-based management, resource status-based management, tax-based management, and bankruptcy management institutions. The performance of these regulatory institutions in a heterogeneous set of physical conditions is demonstrated using a stylized numerical groundwater exploitation example. Results suggest that the benefits to different types of users as well as the sustainability of the CPR vary by the regulator's choice of management institution. More specifically, quota-based management and CPR status-based management institutions can lead to increased benefits to CPR beneficiaries, prolong the CPR's life, and prevent "tragedy of the commons." In contrast, tax-based management institutions may fail to secure sustainable use of the CPRs. Bankruptcy-based management institutions may also be used toward sustainable use of the CPRs and to increase the benefits to the users; however, their overall effectiveness is not as desirable as the quota-based and resource status-based management institutions, especially when enforcing social justice is an issue of concern for the regulator.

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1. Introduction

Common Pool Resources (CPRs) are defined as natural or human-made resource systems characterized by rivalry and non-excludability properties. Given the characteristics of CPRs and their users [1], possible institutions—sets of formal or informal rules governing the users' behavior [2]—for managing CPRs have been suggested in the CPR literature [1,3–7]. These CPR management institutions are classified into three categories [8].

1.1. Non-cooperative management institutions

This category includes the ignorant CPR management planning, based only on individual rationality, in which externalities are completely ignored by the beneficiaries, resulting in the "tragedy of the commons" [9,10]. However, CPR beneficiaries do not always face tragic outcomes in non-cooperative environments, even within the prisoner's dilemma structure [11], normally used for explaining CPR games [12]. In fact, the CPR users can benefit from developing heuristic CPR management plans that are based on learning from past experience to achieve a sustainable CPR. This heuristic behavior allows developing long-term exploitation plans and accounting for the externalities, as opposed to myopic ignorant plans resulting in tragedy of the commons. While heuristic behavior may work in the right direction, it may not satisfy societal objectives and, thus, cooperative management institutions might be formed or exogenous regulatory institutions may be imposed. The analysis of non-cooperative institutions is dealt with in Madani and Dinar [8].

1.2. Cooperative management institutions

In contrast to non-cooperative management institutions under which CPR beneficiaries' decisions are based on individual rationality, under cooperative management institutions, parties base their actions on group rationality. To secure a sustainable use of a CPR, communities or cooperating groups of users are formed and develop exploitation plans, which minimize the externalities and increase the gains to all parties in the long run.[2] The analysis of cooperative CPR management institutions is the subject of Madani and Dinar [13].

1.3. Exogenous regulatory institutions

To prevent overuse and congestion, regulators may intervene by altering exploitations, assigning ownership rights, or enforcing various CPR governing rules. Targeting those beneficiaries who base their actions on individual rationality and ignore the externalities and the long-term effects of their use on the CPR, these external regulatory institutions prevent users from being pushed into a prisoner's dilemma game to avoid the tragedy of the commons. Exogenous regulations are effective only when they are fully enforced (with full obedience on the part of the beneficiaries). Elaboration on the exogenous institutions (regulations) and their effectiveness are the main objectives of this paper.

By introducing various regulatory institutions, and using a stylized numerical groundwater example, the paper recognizes different alternatives to increase the CPR benefits, while preserving the CPR. One of the major contributions of the paper is considering different behaviors of the users in examining the effectiveness of various exogenous regulatory institutions. Considering that exogenous regulatory institutions may impact differently users with different behavioral characteristics, incorporating different behavioral characteristics of the users in policy analysis helps developing effective regulatory institutions to secure sustainability of CPRs. Thus, the paper derives useful lessons for CPR governance and discusses their policy implications.

[2] Within cooperative management institutions CPR users may benefit from markets and trading rights to increase their benefits.

In the next section, various exogenous CPR regulatory institutions are introduced and formulated. In Section 3, a groundwater exploitation problem is introduced. In Section 4, results of application of different exogenous regulatory institutions to the groundwater overexploitation problem is presented and compared. The paper concludes in Section 5, with policy implications for sustainable management of CPRs through external intervention.

2. Exogenous CPR regulatory institutions

Madani and Dinar [8] define the CPR exploitation problem as a pair (e, S) with $e=(e_1, e_2, \ldots, e_n) \geq 0$ and $0 \leq \sum_{i=1}^{n} e_i \leq S$, where e represents the vector of actual exploitations of beneficiaries $i=1, 2, \ldots, n$ and S is the total available (remaining) amount of the CPR to be exploited. The actual utilities of beneficiaries in this problem is represented as an n-tuple $u=(u_1(e_1), u_2(e_2), \ldots, u_n(e_n))$, where $u_i(e_i)$ is the utility of beneficiary i from e_i. The expected utilities of the beneficiaries in this problem is an n-tuple $Eu=(Eu_1(ee_1), Eu_2(ee_2), \ldots, Eu_n(ee_n))$ where $ee=(ee_1, ee_2, \ldots, ee_n) \geq 0$ is the vector of beneficiaries' expected exploitations, and $Eu_i(ee_i)$ is the expected utility of beneficiary i from his expected exploitation ee_i from S (where $\sum_{i=1}^{n} ee_i \leq S$ or $\sum_{i=1}^{n} ee_i \geq S$) such that $e_i \leq ee_i$. All the introduced variables here are time-dependent and can vary over different time-steps of the planning period.

To prolong the CPR's life and prevent tragedy of the commons, the policies implemented by the regulator should be designed to minimize the negative effects of ignoring the externalities and short-term planning by the CPR users [9,14]. Generally, such policies intend to decrease each user's CPR exploitation at a given time-step h ($ee_{i,\ h}$), such that his long-term benefits (over the planning horizon H) from his actual exploitations ($\sum_{h=1}^{H} e_{i,\ h}$) increase. Below, we introduce and formulate a range of regulatory intervening CPR institutions to be implemented by higher-level authorities toward sustainable management of CPRs.

2.1. Quota-based regulatory institution

Under this institution a regulator determines the maximum possible exploitation by each user in a given time step, $Max\ e_{i,\ h}$. With respect to the imposed constraint, the beneficiaries are required to set their expected exploitation lower than the determined maximum amount $ee_{i,\ h} \leq Max\ e_{i,\ h}$. As an example, a regulator may restrict the maximum number of a specific fish that can be caught by fishermen per day. Examples for quota-based groundwater regulations can be found in Knapp and Vaux [15] for groundwater management in California, and in Zekri [16] for groundwater management in Oman.

2.2. Status-based regulation

Similar to the quota-based regulatory institution, the regulator determines a maximum possible exploitation by each user in a given time step. However, instead of setting a constant value for the entire planning horizon, $Max\ ee_{i,\ h}$ is determined based on the status of the system in a given time step, $Max\ ee_{i,\ h}= f(S_h)$, where S_h is the remaining amount of resource to be allocated in time step h. The function $f(S_h)$ is determined by the regulator and can have various forms. For example, a regulator's determined maximum fish to be caught may be season-dependent or may vary by the remaining fish population.[3]

2.3. Tax-based regulation

Regulators impose taxes on the beneficiaries to make exploitation more expensive and drive reduction. These taxes can be imposed in different forms. A tax may be imposed to increase the exploitation costs to the beneficiaries (e.g., raising the price of fishing permit, fishing devices, or charging the fishermen an amount per fish caught). In that case $Tax_{i,\ h}=Co(e_{i,\ h}) \times (1+\alpha)$ where $Tax_{i,\ h}$ is the tax that beneficiary i

[3] Status-based management is a more flexible version of quota-based management under which the regulator might change the regulation based on the latest status of CPR or tries to control the withdrawals by relying on some status indicators (e.g. groundwater drawdown level).

should pay in time-step h, α is the tax rate, and $Co(e_{i,h})$ is the cost of exploiting e in h by i. A tax may also be imposed on the utility gained from exploitation (e.g., each fisherman should pay some percentage of his revenue to the regulator protecting the fishery), which could be parallel to a Pigouvian tax. In that case $Tax_{i,\ h} = \beta \times u_{i,\ h}(e_{i,\ h})$, where β is the utility tax rate. As another alternative, a tax may be imposed directly on beneficiaries' exploitations (e.g., each fisherman should return some percentage of his catch to the regulator or the river). In that case $Tax_{i,\ h} = \mu \times e_{i,\ h}$ where $Tax_{i,h}$ is the tax beneficiary i should pay in h and μ is the exploitation tax rate. Examples of application of this institution in groundwater management include Knapp and Vaux [15], Ward [17], and Shah et al. [18].

2.4. Bankruptcy-based management

The regulator treats the CPR as a bankrupt entity with total debt more than the total financial assets to be credited among the creditors. In that case, the expected exploitation of each beneficiary in a given time step, $ee_{i,\ h}$ should be reduced by some amount, which can be calculated using different bankruptcy methods available in the literature [19–27]. For example, using the proportional rule,[4,5] the regulator may reduce each beneficiary's expected exploitation by Ω (say 10%), where the reduced expected exploitation of beneficiary i in time h ($ree_{i,\ h}$) can be calculated by reducing $ee_{i,\ h}$ by Ω ($ree_{i,\ h} = (1-\Omega) \times ee_{i,\ h}$). Or, using the Constrained Equal Award (CEA) rule,[6] $ree_{i,\ h}$ can be set equal to minimum of $ee_{i,\ h}$ and ø ($ree_{i,\ h} = min(ee_{i,\ h}, ø)$), where $\sum_{i=1}^{n} ree_{i,\ h} = (1-\Omega)\sum_{i=1}^{n} ee_{i,\ h}$.

To explain how the introduced management institutions can be applied in practice to CPR management, a groundwater problem is presented in the next section.

3. Groundwater exploitation problem

The complexity in estimating the externalities, and monitoring and regulating groundwater withdrawals makes this resource an interesting CPR to study [28–33]. Here, the groundwater exploitation problem introduced by Madani and Dinar [8] is presented briefly for application of the introduced regulatory institutions.[7] Readers are referred to Madani and Dinar [8] for full details of the model. The groundwater exploitation problem is mathematically formulated as:

$$C_p = (us + v + d_{h-1})Q \tag{1}$$

$$C = C_p + C_{Tech} + C_{other,\ x} \tag{2}$$

$$C_{other,\ x} = i_x l_x^2 + j_x l_x + k_x \tag{3}$$

$$Y_x = (p_x l_x^2 + q_x l_x)Q_x \tag{4}$$

$$R = \sum_x z_x Y_x \tag{5}$$

$$P = R - C \tag{6}$$

[4] The basis for justice under this rule, a principle favored by ancient philosophers [19], is the enforcement of reduction of exploitations among all users by the same proportion (Ω).

[5] Proportional cutback is one of the widely applied methods for groundwater regulation around the world (e.g. California, Iran).

[6] The CEA rule—an ancient rule, adopted by rabbinical legislators—awards the same sum to all CPR beneficiaries as long as this sum is lower than their expected withdrawal [19].

[7] While this paper uses groundwater as a CPR example, the derived policy insights and conclusions could be generalized to all CPRs with subtractability and non-excludability properties. In fact, groundwater is one of the complex CPRs to study, due to the non-linear externalities (i.e., the effect of withdrawal from one well on the neighboring wells varies non-linearly based on the distance of the wells, the amount of withdrawal, and other hydrogeologic characteristics of the aquifer). Nonetheless, similar to other CPRs, the rival characteristic of groundwater is linear (i.e., one unit withdrawal leaves one unit less for the other users).

$$Z = \int_0^H Pe^{-rh} dh \tag{7}$$

where C_P=groundwater pumping cost; Q=total well discharge; s=groundwater drawdown, resulting from Q; d_{h-1}=well water depth in the at the end of previous time step $(h-1)$; u and v=cost parameters C_{Tech}=onetime initial investment for irrigation technologies, represented by the annual-equivalent cost; $C_{Other,\ x}$=cost of seeds, fertilizer, planting, harvesting, etc. l_x=area under irrigation for growing crop x i_x, j_x, and k_x=cost parameters which depends on the crop type (x); Q_x=amount of water used for irrigation of crop x; Y_x=total yield of crop x; p_x=yield parameter which depends on the crop type (x); q_x=yield parameter which depends on the crop type (x); R=revenue gained through selling crops at the end of the growing season; z_x=price per weight unit of the crop x; r=time-step dependent discount rate; P=farmer's profit is a given time step; Z=total present value of farmer's profit; and H=length of the planning horizon.

The groundwater drawdown in a single well during time t (representing the length of the time period being considered) at a given distance from the center of a well with discharge of Q in an aquifer is approximated using Eq. (8) [34]. Eq. (8) varies in a and b by the considered distance from the pumping location. Given the distance, aquifer transmissivity (T), and storativity, coefficients a and b can be estimated by regression of this equation against the predicted drawdown through the Theis equation for groundwater drawdown [35]

$$s = \frac{Q}{4\pi T}(a \ln t + b) \tag{8}$$

with π being the geometrical constant having the value of 3.14.

We use the numerical example from Madani and Dinar [8] as a benchmark[8] for comparing the performance of different external intervening institutions for regulating CPRs. This example includes three farmers, each operating one well (i=A, B and C), located on three neighboring farms with different areas, with lot A being the largest (giving an opportunity to Farmer A to benefit from economies of scale in production) and lot C being the smallest. The farms are located on a sloped land, creating a difference in water depths (or pumping costs) at the three wells, with well A having the maximum water depth (highest pumping cost per unit groundwater withdrawn) and well C having the minimum water depth. Each farmer is assumed to have two crop options. Tables 1–3 present the values of farmer-dependent, crop-dependent, and independent parameters used in the numerical benchmark example [8], respectively.[9]

In this problem, each farmer independently tries to maximize the present value of his profit over his planning horizon, creating externalities for others. Therefore, their actual profit normally differs from the expected profit, based on Eqs. (1–8). This is mainly due to farmers' inability to accurately estimate the groundwater drawdown in their wells in absence of information about other neighboring farmers' groundwater exploitation strategies. Indeed, when multiple wells are present, Eq. (8) does not allow for taking into account the mutual effects of discharges at neighboring wells (externalities). While due to lack of information, some farmers may use Eq. (8) for planning, the actual drawdown can be calculated using Eq. (9) [34]. This equation varies by distances of the drawdown measurement locations from the pumping locations (coefficients a_{ii}, b_{ii}, a_{ij}, and b_{ij} depend on the relative locations of other wells with respect to well i).

$$s_i = \frac{Q_i}{4\pi T}(a_{ii} \ln t + b_{ii}) + \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{Q_i}{4\pi T}(a_{ij} \ln t + b_{ij}) \tag{9}$$

Wells normally benefit from natural recharge and return flows from water use on the corresponding farm as well as the water use in neighboring farms. Thus, in calculating the drawdown, using Eqs. (8) or (9), net well

[8] Madani and Dinar [8,13], respectively, use the same example in studying the effects of different cooperative and non-cooperative management institutions on the status of the CPR and the benefits of the users.

[9] The specifications of the benchmark groundwater example are arbitrary.

Table 1
Values of farmer-dependent parameters (Madani and Dinar [8]).

Farmer	Parameter												
	l (ha)	d_0 (m)	a_{iA}	a_{iB}	a_{iC}	b_{iA}	b_{iB}	b_{iC}	Q_r (m^3/year)	Θ	$\omega_{i,A}$	$\omega_{i,B}$	$\omega_{i,C}$
A	40	20	9.125	5.423	3.640	140	100	50	1000	0.08	–	0	0
B	28	14	5.423	9.125	6.684	100	140	115	900	0.07	0.085	–	0
C	15	9	3.640	6.684	9.125	50	115	140	750	0.06	0.035	0.075	–

Table 2
Values of crop-dependent parameters (Madani and Dinar [8]).

Crop	Parameter					
	P (Ton/m^3/ha^2/year)	Q (Ton/m^3/ha^2/year)	I (\$/ha^2/year)	J (\$/ha/year)	K (\$/year)	Z (\$/Ton)
1	-2.49×10^{-10}	0.0256	-9.8175×10^{-3}	892.5	2.769	150
2	-7.51×10^{-11}	0.0280	-9.8485×10^{-3}	689.4	0.611	134

Table 3
Values of independent parameters (Madani and Dinar [8]).

Parameter									
A	b	t*	T (m^2/day)	U (\$ m^{-3}/m^{-1})	V (\$ m^{-3})	R (%/year)	C_{Tech} (\$)	Qe_i (m^3/year)	H (years)
9.125	140	365	6960	7.2	*10*	*0.05*	*0*	*0*	*50*

* t should be set equal to 365 in Eqs. (8) and (9) to calculate the drawdown over one time-step (h).

discharges should be used which can be calculated as

$$Q_{i,Net} = Q_i - \left(Q_{i,r} + \theta_i Q_i + \sum_{\substack{j=1 \\ j\neq i}}^{n} \omega_{i,j} Q_j\right) + Qe_i \tag{10}$$

where Q_i=pumped discharge of well i; $Q_{i,\,r}$=natural recharge of well i; θ_i=ratio of return flow from water use on farm i to well i; $\omega_{i,\,j}$=ratio of return flow from water use on a farm j to well i; and Qe_i=evaporative losses of well i.

In absence of information about neighboring farmers' water withdrawal plans, farmers cannot estimate the return flows from neighboring farms (positive externality), failing to accurately estimate the net well discharge based on Eq. (10).

For solving the benchmark problem without regulator's intervention, an optimization model is run for each farmer independently, using Eqs. (1)–(8). In this case, net well discharge is calculated using Eq. (10) without the recharge from neighboring well components. As will be discussed in the next section, depending on their behavioral characteristics, farmers can chose different planning horizons for their optimization model and may use different heuristics for improving their estimation of profit and groundwater drawdown by modification of profit and drawdown estimation equations. The developed strategies by farmers' independent optimization models are then fed into a simulation model which calculates the actual drawdowns and profits of each farm using Eqs. (9) and (10).

To compare the effectiveness of various exogenous CPR regulatory institutions and highlight the difference between them, different exogenous groundwater regulatory institutions are developed and applied to the numerical example. Madani and Dinar [8] numerically proved a positive relationship between CPR's sustainability (lifetime) and long-term benefits of its beneficiaries. Their results show that farmers can benefit from sustainable use of groundwater and increase their long-term benefits by reducing their short-term withdrawal, keeping groundwater depth and pumping costs at a reasonable level for a longer period. While can be beneficial in the short-run, aggressive withdrawal, makes the resource unsustainable by lowering the groundwater level early on, resulting in lower benefits over the long-run due to increased groundwater depth and pumping costs. With understanding the direct relationship between groundwater's sustainability and long-term benefits of the users, the regulator's objective is to increase the long-term benefits (maximize the social welfare) by adopting exogenous regulatory institutions that control users' withdrawal. The regulator tries to keep the groundwater depth and average pumping cost within a reasonable level to make farming profitable to all farmers in the long run.[10] The regulator evaluates the effectiveness of exogenous regulatory institution based on the following criteria:

(a) *Social welfare*: In order to be effective, an exogenous regulatory institution should increase social welfare (sum of farmers' benefits) in the long-term (over the planning period).
(b) *Social justice*: While increasing social welfare is a major objective of regulatory intervention, institutions that result in increasing wealthier farmers' benefits at the expense of less wealthier farmers' losses are considered ineffective, even if they increase the social welfare overall. The regulator is mostly concerned about formation of business monopolies in which weak farmers (with low level of wealth or small farms in this case) might have to quit farming due to the undesirable externalities created by strong farmers (with high levels of wealth or large farms in this case).
(c) *Robustness*: With the expectation that users with different behavioral characteristics are affected differently by regulatory intervention, the regulator prefers institutions that serve the majority of behavioral classes. Given that the regulator cannot exactly determine the behavioral characteristics of all users, the interest is in lowering the risk of failure of an intervention in meeting the social welfare and social justice criteria, by targeting majority of the behavioral types.

4. Groundwater governance models and results

While a regulator develops various institutions to manage CPRs, responses of beneficiaries to these institutions vary as they may use a range of individual heuristic CPR planning and management institutional approaches for exploitation. Table 4 presents several of such management institutions, reflecting different types of behaviors that may be used by non-cooperative users. Choice of the beneficiaries' management institutions (type of behavior) depends on the characteristics of the beneficiaries, mainly their foresight (how long they are planning for) and ignorance level (if they consider the externalities or not). The performance of the CPR improves as the beneficiaries become less ignorant[11] and less myopic.[12] Out of these two factors, long-term planning has shown to be more important in achieving a sustainable CPR [8]. Based on their choice of management institutions, beneficiaries use different objective functions and consider different planning horizons to develop their exploitation policies. The last column of Table 4 illustrates how groundwater beneficiaries modify their planning model based on their behavioral characteristics in Madani and Dinar [8].

We explore the various exogenous regulatory institutions and examine their sensitivity to the non-cooperative management institutions (type of behavior) adopted by the beneficiaries using a specific numerical example. Six groundwater regulatory institutions are presented, based on the introduced exogenous regulatory CPR management institutions. Here, it is assumed that the regulator can fully enforce

[10] For simplicity, we are not considering groundwater quality and land subsidence issues here. In practice, lower levels of groundwater can result groundwater quality issues that restrict crop options to the farmers or make farming generally infeasible. Moreover, lower groundwater levels can result in land subsidence and its associated costs.

[11] An ignorant beneficiary neglects externalities when developing resource exploitation and management plans.

[12] A myopic beneficiary is more interested in maximizing short-term profits without consideration of long-term impacts of his short-term decisions.

Table 4
Non-cooperative groundwater management institutions (types of behavior) (Madani and Dinar [8]).

Behavior type	Description	Groundwater planning model
Ignorant myopic management (IMM)	Decision maker (DM) develops a short-term plan with no consideration of externalities.	DM maximizes Eq. (7) and plans for 1 year only at the beginning of each time step.
Smart myopic management with drawdown penalty	DM develops a short-term plan and tries to consider the externalities based on his past experience (the difference between the perceived and actual drawdown in previous steps)	DM adds a drawdown penalty to the IMM objective function and plans for 1 year only at the beginning of each time step. The penalty value is updated based on performance in predicting drawdown in previous time steps.
Smart myopic management with profit penalty	DM develops short-term plans and tries to consider the externalities based on his past experience (the difference between the perceived and actual profit in previous steps)	DM adds a profit penalty to the IMM objective function and plans for 1 year only at the beginning of each time step. The penalty value is updated based on performance in predicting profit in previous time steps.
Fixed ignorant non-myopic management	DM develops a plan with fixed decision variables for a long-term with no consideration of the externalities.	DM uses the IMM objective function and plans for 50 years with fixed decision variables (pumping rate, area under cultivation, type of crop, etc.) for the entire planning horizon.
Variable ignorant non-myopic management (VINMM)	DM develops a plan with variable decision variables for a long-term with no consideration of the externalities.	DM uses the IMM objective function and plans for 50 years. Decision variables are not fixed and can change over time-steps.
Smart non-myopic management	DM develops a long-term plan with variable decision variables and tries to consider the externalities by continuous revision of his long-term plan.	DM updates his decisions by running VINMM for 50 years at the beginning of each time step.

the desired institution. While the regulator cannot reliably predict the exploitation strategies and behavioral characteristics of the farmers, it can comprehensively measure/control/monitor their withdrawals, gains, and other decision variables and strategies if required by the adopted regulatory exogenous management institution.

To follow the enforced regulation under each exogenous regulatory groundwater management institution farmers make appropriate changes to their independent profit maximization models, e.g. by adding a maximum allowable withdrawal constraint or by adding an electricity tax cost component. The modified optimization models are run independently and the overall impact of the exogenous regulatory groundwater management institution is evaluated by running the simulation model using the outputs of the independent optimization models.

To examine the response of different types of users (six types as presented in Table 4) 36 models were required.[13] We ran each model under four different intervention scenarios, representing different levels of the intervening regulations, resulting in 144 model runs. Each yearly-based model was run for a 50-year planning period (which is reasonably long, considering the computational limitations) to examine the long-term benefits of the various types of users to externally intervening policies. Below, these models are presented together with discussion and comparison of the obtained modeling results.[14] Readers are referred to our working paper [36] for detailed modeling results.

[13] Here, we only examine cases in which all farmers apply the same management institution and are homogenous in their behavioral characteristics.

[14] Given the number of decision variables in each model run, detailed presentation of all modeling outputs would not be possible. Here, the interest is in big picture of the problem for developing policy implications based on the major findings. Therefore, we only report farmers' long-term benefits, reflecting the performance of a groundwater management institution. As indicated by Madani and Dinar [13,8] higher benefits are achieved through sustainable use of the CPR and prolonging extending its life.

Different levels of intervention under each regulatory management institution are used as different “what-if?” scenarios to help evaluate the effectiveness of the institution based on the three regulator's effectiveness evaluation criteria (social welfare, social justice, and robustness). While the intervention increments have been selected arbitrarily and may not necessarily reflect the optimal level of intervention,[15] they have been selected from a near-optimal range[16] so that the intervention effectiveness can be evaluated. Given that interventions belong to the near-optimal range, it is reasonable to compare the effectiveness of different institutions besides evaluating their overall performances. A similar approach was used by Dinar at al. [37] in the case of regulating drainage water pollution in the San Joaquin Valley, California.

4.1. *Quota management*

To control groundwater withdrawal, the regulator may interfere through a quota management institution under which a maximum allowable discharge is determined. In this case, each farmer adds a constraint to his profit optimization model to ensure that his groundwater withdrawal does not exceed the maximum quota. Fig. 1 indicates how the different types of farmers respond to different levels of groundwater quota, in the numerical example. Here, Farmer A benefits from the highest profit under all cases, due to having the largest farm size which gives him the opportunity for benefiting from economies of scale (lower marginal cost of production). Although this farmer has the highest pumping head (average pumping cost), due to a large farm size, the benefits of production outweigh his production costs (including pumping costs). Therefore, this farmer can obtain the highest profit among the three farmers. The opposite holds true for Farmer C with the smallest farm, although he has the lowest pumping head.. Moving from top to bottom in Figs. 1–6, generally the profits of the farmers increase as they get less myopic and more considerate of the externalities.

Results indicate that regulating groundwater withdrawals under the quota management institution has a great potential for increasing social welfare. However, over-restriction can result in losses for farmers with certain type of behavior when their well's recharge rate is more than the allocated quota (e.g. non-myopic Farmer A when the maximum allowable extraction reaches 1000 m^3/year, which is less than the recharge rate of well A).

The sensitivity of the users to different levels of regulations (here, different discharge limits) varies by user type. The ignorant myopic decision makers are the most sensitive and benefit the most from the imposed restriction, compared with the considerate non-myopic users that are the least sensitive to the imposed restriction. Therefore, the quota management institution is most effective when the users are more myopic and ignorant, which is typical to CPR user communities. Both Farmers B and C with lower wealth levels (smaller farms) benefit from quota management under various behavioral types. Therefore, this management institution satisfies the social justice criterion of the regulator. Given that quota management generally serves the majority of behavioral classes, it can be considered as a robust CPR management mechanism. Satisfying all three criteria of the social planner, quota management is an effective tool for sustainable CPR management and for increasing long-term benefits of its users.

It is noteworthy that the modeling results [36] suggest that due to the unaccounted externalities and myopic planning, in most cases the actual gains of the farmers are less than what they perceived.[17] Nevertheless, the actual gains are more than the perceived gains for all types of farmers

[15] Future studies might focus on identifying the optimal level of intervention based on regulator's objectives.

[16] The modeling exercise involved a trial and error step in which different levels of intervention under each institution were tested in order to detect the near-optimal region. Intervention intervals under each institution were also selected through trial and error such that the results are not highly similar for different intervention levels. This helped with observing trends and better understanding of the sensitivity of institutions' performance to different intervention levels.

[17] Assuming that farmers have no information about groundwater exploitation strategies of other farmers, they cannot use Eq. (9) for direct and accurate estimation of the externalities. Therefore, when making decisions using different objective functions and planning periods (Table 4) they use Eq. (8) to develop their management plan and determine their perceived (expected) profit at the beginning of the planning period. Based on their developed plans, their actual gains at the end of the planning period can be then determined using Eq. (9).

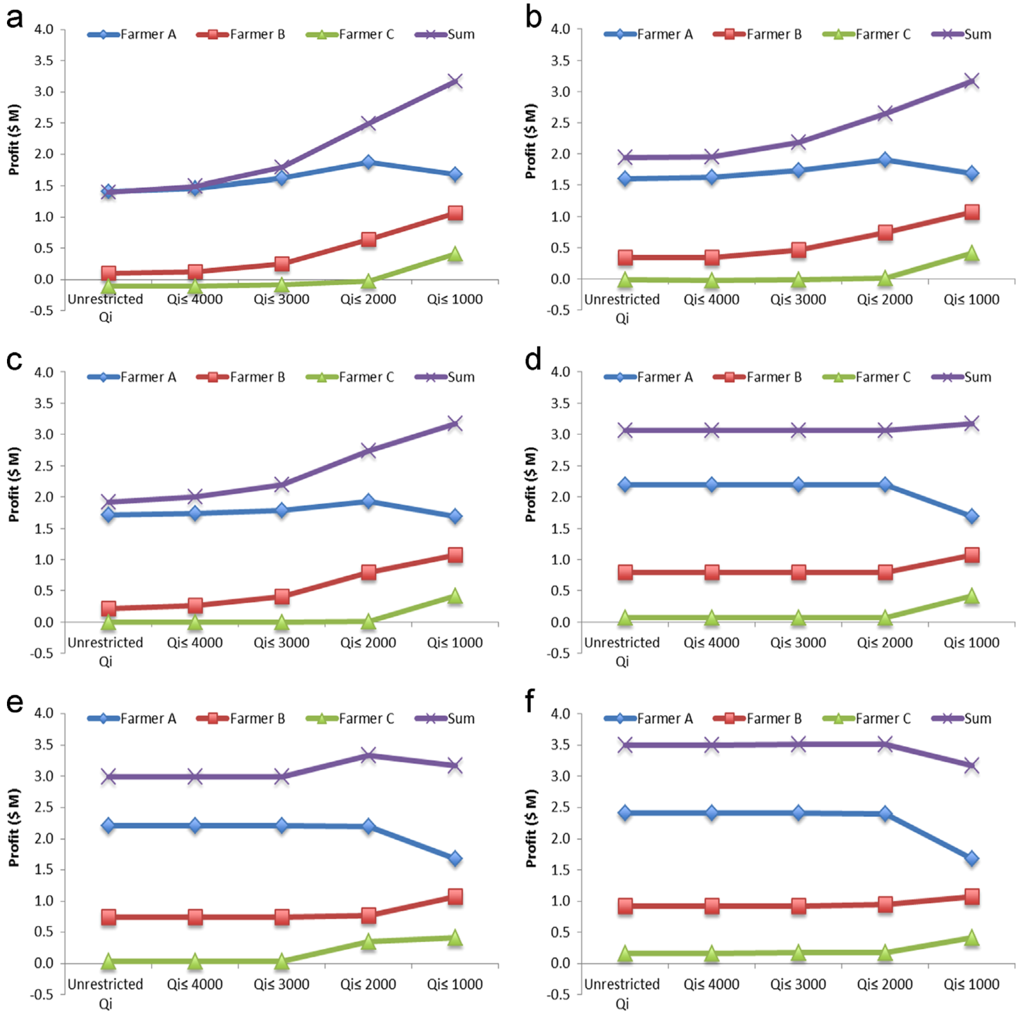

Fig. 1. Quota management institution under different levels of intervention: total profits of farmers with different types of behaviors (a—Ignorant myopic management, b—Smart myopic management with drawdown penalty, c—Smart myopic management with profit penalty, d—Fixed ignorant non-myopic management, e—Variable ignorant non-myopic management and f—Smart non-myopic management).

when they get highly restricted. Also, the difference between the actual gain and perceived gain of the farmers decreases when they face higher restrictions, implying that the effects of not considering the externalities and myopic planning are minimized when stronger restrictions are enforced by regulatory authorities.

4.2. Groundwater-status management

Groundwater level or water depth in the well is a reliable factor in determining the status of the groundwater resource. Therefore, it can be used as a basis for management by the regulator. Under the groundwater-status management institution, the regulator may impose restrictions on the maximum possible drawdown in the wells. In this case, each farmer adds a constraint to its profit optimization model to ensure that the groundwater drawdown in his well (estimated based on Eq. (8)) is less than

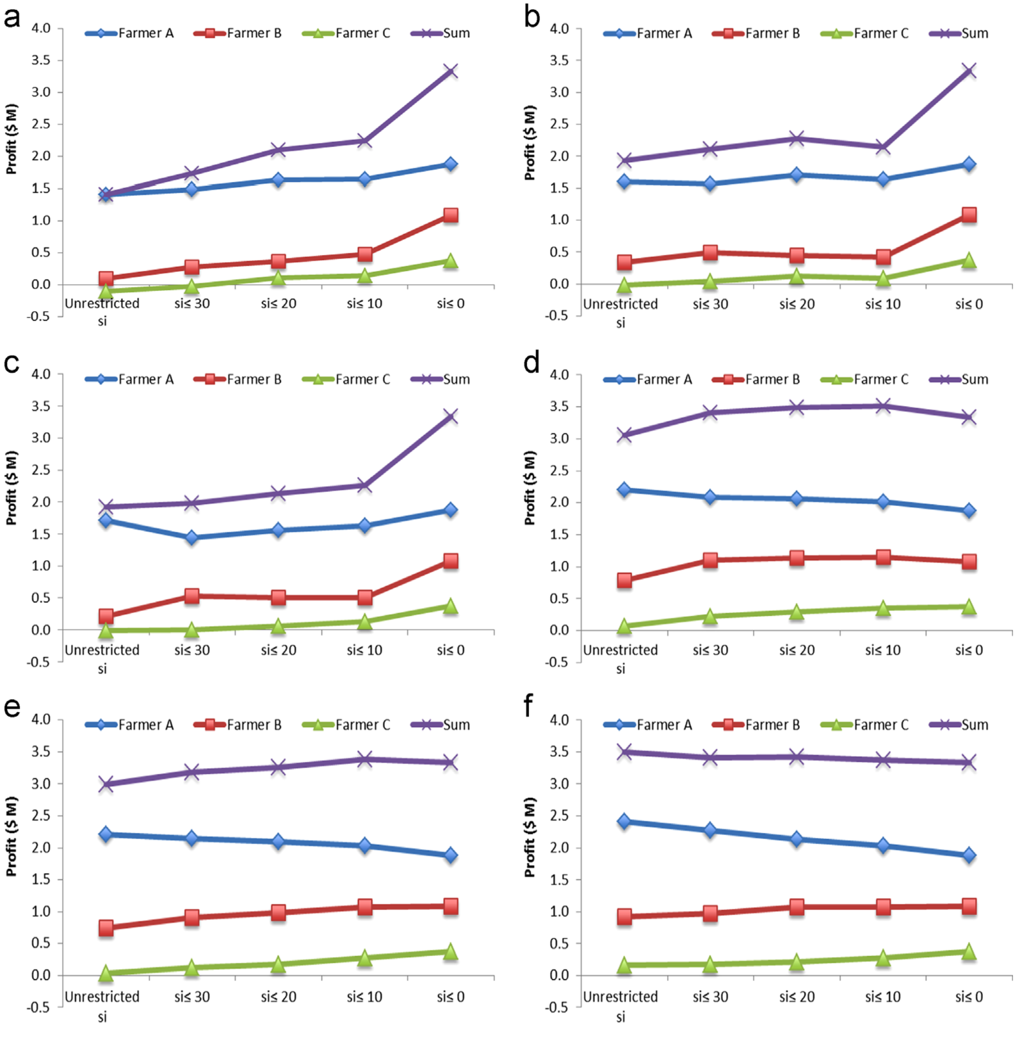

Fig. 2. Groundwater status management institution under different levels of intervention: total profits of farmers with different types of behaviors (a—Ignorant myopic management, b—Smart myopic management with drawdown penalty, c—Smart myopic management with profit penalty, d—Fixed ignorant non-myopic management, e—Variable ignorant non-myopic management and f—Smart non-myopic management).

the maximum possible drawdown. Fig. 2 presents the results of different groundwater-status management models, under different levels of interference through the groundwater drawdown management institution in the numerical example. Here, it is assumed that the regulator interferes by setting the maximum allowable groundwater drawdown. Results show how long-term benefits for the different types of farmers change in response to different levels of drawdown restrictions.

Generally, the results under this institution are more or less the same as the results obtained under the groundwater quota management institution. Regulating through a groundwater-status management institution has potential to increase social welfare, especially when users are myopic and ignorant. Only in case of non-myopic smart management, status-management does not result in increased social welfare, due to losses of the wealthy farmer. Nevertheless, this management institution can still help the poorer non-myopic smart users.

Although, this management institution does not serve the wealthy farmer (Farmer A) when he acts non-myopically, it is an attractive institution based on the social justice criterion as it helps Farmers B and C with lower level of wealth to increase their long-term benefits. Its performance, however, is not as good as quota management when increased benefits to Farmer A under non-myopic behavior is expected.

Farmers are sensitive to the regulator's interference level (here, different limit levels), with ignorant myopic decision makers being the most sensitive. Similar to the previous case, this type of farmer benefits the most from the imposed restrictions, even with over-restriction ($s_i \leq 0$). The opposite is true for the smart non-myopic users, who are less sensitive to the imposed restrictions. This management institution is robust as it serves the majority of behavioral classes. Overall, status-based management can be considered an effective regulatory institution given that it satisfies all three effectiveness criteria of the regulator.

4.3. *Tax-based management*

As discussed earlier, to prevent overdraft of CPR resources, taxes may be imposed in different forms. Here, we applied different levels of electricity price and groundwater withdrawal taxes to examine the farmers' response in the numerical example.

4.3.1. *Electricity tax*

Fig. 3 presents how farmers' long-term benefits from using groundwater change by various electricity tax levels. Electricity tax is imposed on the farmers to increase the pumping cost with the goal of reducing their groundwater extraction. In this case, farmers modify the pumping cost equation (Eq. (1)) to account for the imposed electricity taxes. Application of this type of tax to groundwater management in California is discussed in Knapp and Vaux [15] and Dinar [38]. In a relevant study, Scott and Shah [39] discuss how the elimination of energy subsidies can affect groundwater exploitation in Mexico and India.

Results of our analysis indicate that electricity taxing (when implemented as a flat tax, as opposed to a block rate tax) is ineffective in preventing groundwater over-exploitation and increasing social welfare (except for few cases). The presented results do not reflect the total amount of collected tax that may be re-distributed among the users. Direct return of the collected tax can encourage aggressive behaviors and make the behaviors fully insensitive to taxing. However, it is reasonable to argue that although flat monetary taxation does not help prolong the CPR's life, in practice, the collected tax can contribute to social welfare if redistributed indirectly. Also, due to the generated revenue taxing institutions can be enforced easier than other regulatory institutions in practice.

The findings regarding electricity taxation in this study may not hold when flat electricity taxation is replaced with tiered taxation, which is more efficient in forcing the CPR users to change their behavior, resulting in less CPR withdrawals [40]. For comparison and finding the efficiency of tiered taxation, future studies may consider the effects of tiered taxing on groundwater withdrawals.

When smart non-myopic farmers are subject to higher level of taxation (Fig. 3F) Farmer C has to quit farming due to high pumping costs. The other two farmers can take advantage of Farmer C's exit and increase their benefits. Although the total benefits obtained by the three farmers increase under higher electricity tax rates for smart non-myopic farmers, this type of management will benefit the users with higher wealth levels, who can stay in the business, more than the poorest users, who quit as a result of increased costs. Therefore, this type of taxation results in higher benefits only to a certain group of users, violating the social justice rationale. To compensate for this effect, the collected taxes may be transferred to the users with lower wealth level. However, this type of institution cannot secure the sustainability of the CPR, even if it is associated with some economic efficiency improvements in case of tax returns.[18]

[18] Similar to electricity taxing, imposing taxes on profit is not very effective in prolonging the resource life, because it is not related to the quantity extracted. It only reduces the benefit (profits) to the users without giving them incentives to lessen the withdrawal. For this reason, profit taxing was not tested here.

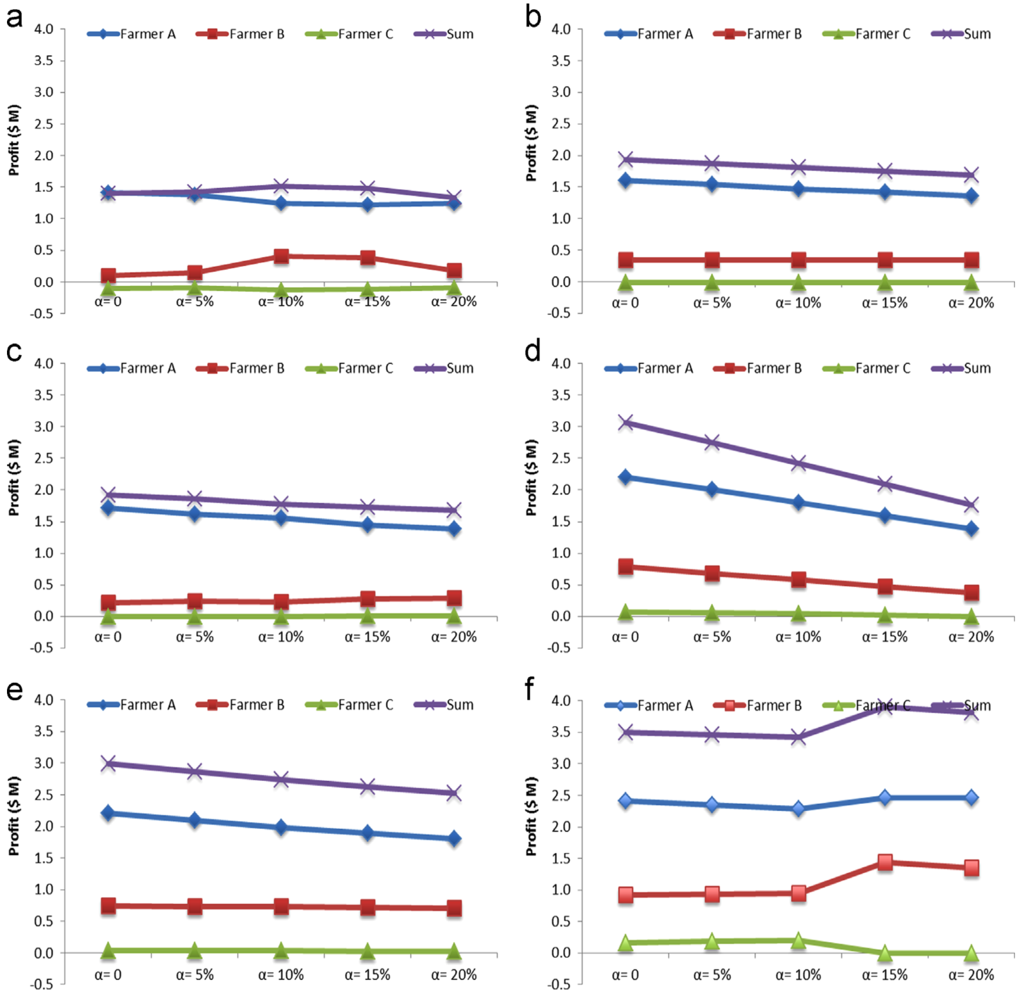

Fig. 3. Electricity taxation institution under different levels of intervention: total profits of farmers with different types of behaviors (a—Ignorant myopic management, b—Smart myopic management with drawdown penalty, c—Smart myopic management with profit penalty, d— Fixed ignorant non-myopic management, e—Variable ignorant non-myopic management and f—Smart non-myopic management).

4.3.2. *Withdrawal tax*

Fig. 4 shows how farmers' long-term benefits from using groundwater change by altering groundwater taxation levels. Groundwater tax is the amount of water each farmer needs to put back in his well after pumping and bearing the associated pumping costs. This is relatively similar to imposing groundwater replenishment tax on the farmers, in which they are required to pay the cost of replacing the groundwater they use (e.g., Coachella Valley Water District in California and Central Arizona Groundwater Replenishment District). In this case, the available water for irrigation or the net water withdrawn (used in Eqs. (4), (9), and (10)) is less than the amount of withdrawn water used in the Eqs. (1) and (4).

Results indicate that users' gains are the highest under the case of zero groundwater taxing. Therefore, flat groundwater taxing is not an effective tool in preventing groundwater over-exploitation to increase the long-term benefits of the users. This is due to the pumping costs. In fact, increasing the groundwater tax rate results in less profit for the users, as they cannot use the exploited water for which they have already paid the extraction costs.

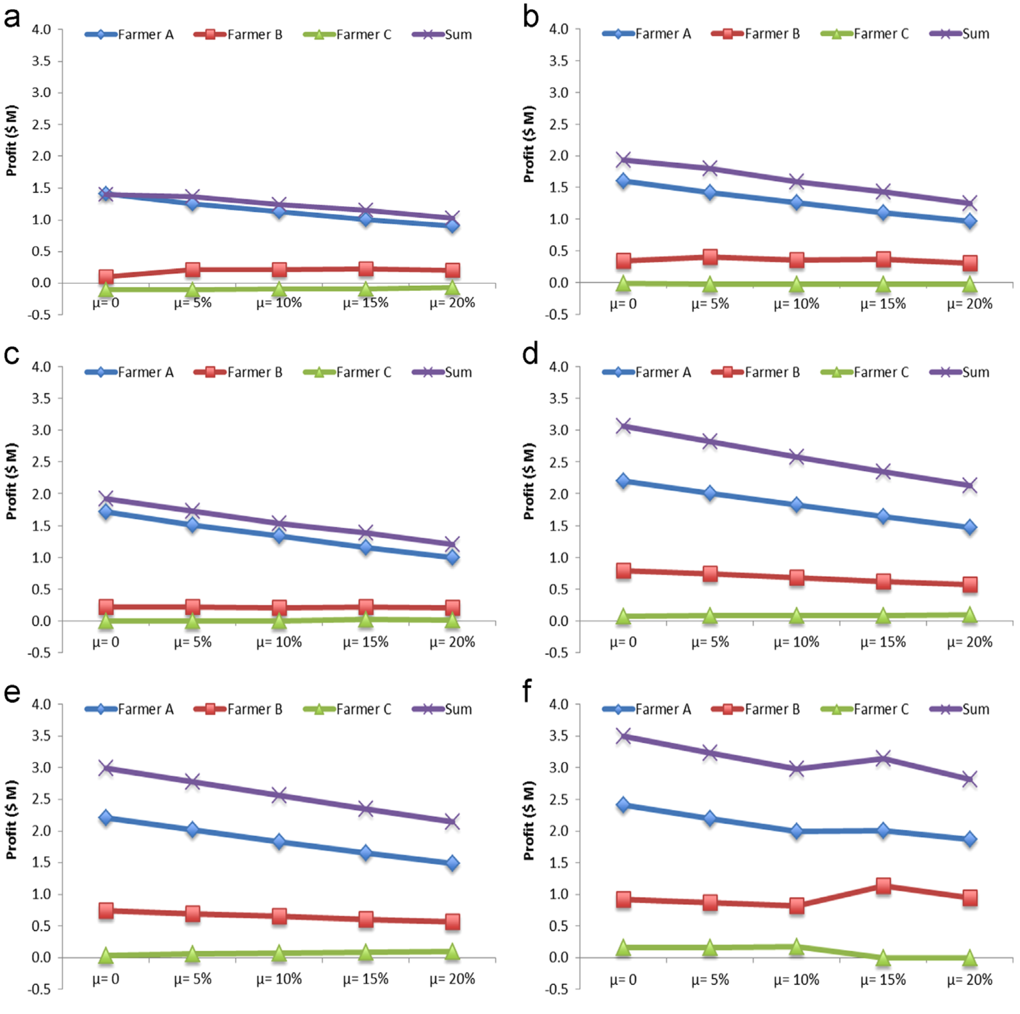

Fig. 4. Groundwater taxation institution under different levels of intervention: total profits of farmers with different types of behaviors (a—Ignorant myopic management, b—Smart myopic management with drawdown penalty, c—Smart myopic management with profit penalty, d—Fixed ignorant non-myopic management, e—Variable ignorant non-myopic management and f—Smart non-myopic management).

Further studies are required to examine the most effective flat taxing method. When monetary taxing methods are applied, the collected taxes may be used by the regulator for enforcing regulations and monitoring groundwater withdrawals. Therefore, taxation may be used in some cases for better management of the resource, especially in cooperative frameworks in which the collected taxes can be invested towards better management of the resource.[19]

[19] It is noteworthy that we also examined how imposing taxes on revenues can alter users' behaviors, which included 24 additional model runs (four different levels of revenue taxes applied to six different behavioral types). Given that this taxing institution was also ineffective, the results are not presented here. The obtained results [37] suggest that users are better off without government interference in the form of flat revenue tax collection, implying that revenue taxing is not an effective tool to achieve sustainable CPRs. While the collected taxes can be returned to the users, revenue taxing will just increase their benefits from the CPR with no serious effect on their behavior (the maximum tax return will result in the total benefits becoming equal to the zero-tax case), and resulting in a failure in securing a sustainable CPR.

4.4. Bankruptcy management

In response to overexploitation and unsustainable use of groundwater, governing authorities may interfere by forcing the users to reduce their aggregated groundwater withdrawal by Ω. In that case, the main challenge is to find a fair allocation of Ω among the users. This problem is normally solved using bankruptcy methods [19–21]. Here, we solved the numerical problem using two bankruptcy methods, namely the proportional and the Constrained Equal Award (CEA) rules.

4.4.1. Proportional bankruptcy

Under this rule, users are forced to reduce their planned exploitation by Ω at the beginning of each time step. In this case, farmers develop their strategies without any change to their optimization model. Then the proportional bankruptcy rule is applied to the planned groundwater withdrawal

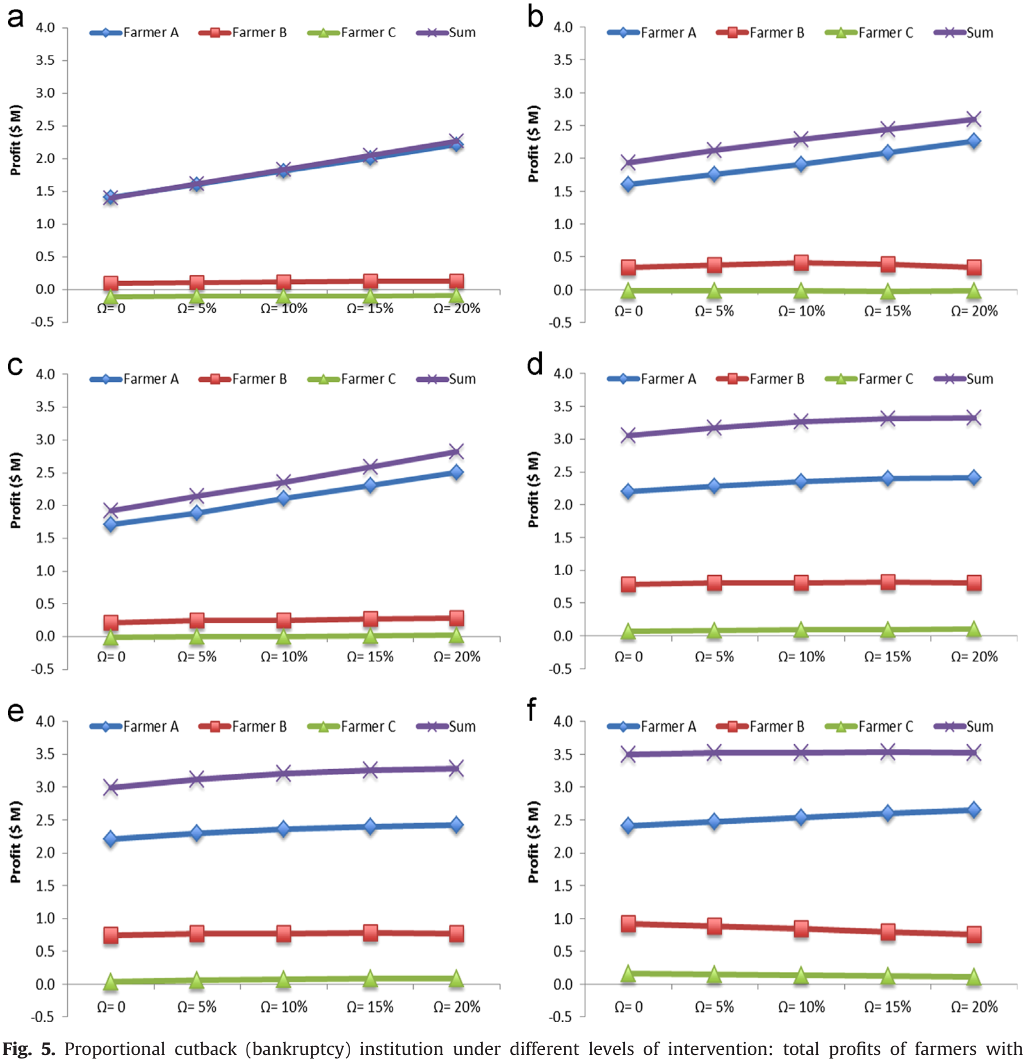

Fig. 5. Proportional cutback (bankruptcy) institution under different levels of intervention: total profits of farmers with different types of behaviors (a—Ignorant myopic management, b—Smart myopic management with drawdown penalty, c—Smart myopic management with profit penalty, d—Fixed ignorant non-myopic management, e—Variable ignorant non-myopic management and f—mart non-myopic management).

rates to determine the actual groundwater withdrawal rates. The actual withdrawal rates are used in running the simulation model to evaluate the effects of the proportional bankruptcy rule. Fig. 5 indicates the results of the model runs under the proportional rule for different Ω values.

Results suggest that proportional cutbacks can be used as an effective tool for prolonging the life of the CPRs and increasing social welfare. While over-restriction may result in reduced benefits to some users under certain types of behavior (e.g. Farmers B and C in Fig. 5f) this institution satisfies the social justify criterion in other cases. Nevertheless, the wealthiest farmer (Farmer A) benefits the most from implementation of proportional bankruptcy. So, it can be argued that this institution does not necessarily result in a fair distribution of incremental benefits of intervention. This management institution is fairly robust as it serves the majority of behavioral classes. Therefore, overall, this management institution is effective in prolonging the CPR's life and increasing the long-term benefits of its users. Nevertheless, its quality of performance is not as desirable as quota-based and status-based management institutions, especially because it fails to significantly benefit the less wealthier beneficiaries.[20]

4.4.2. *Constrained equal award (CEA) bankruptcy*

Theoretically, this rule intends to enforce justice by satisfying the less wealthier beneficiaries, who may lose more from share reduction, before satisfying the rich beneficiaries, who may not bear significant losses from share reduction due to their high wealth level. The calculation procedure is similar to the proportional bankruptcy case. But in this case, the actual withdrawal rates are determined using the CEA rule instead of the proportional rule.

Fig. 6 indicates the results of model runs when the farmers were forced to decrease their total planned withdrawal by different Ω values, based on the CEA bankruptcy rule. Results indicate that unlike the proportional bankruptcy institution, the CEA bankruptcy institution cannot generally increase social welfare for all types of farmers. This institution increases social welfare only for myopic users. This, it is neither an effective, nor a robust regulating institution. While this institution seeks supporting the these users lower wealth levels, its effects on users (e.g. Farmer C, for example) are mixed and sensitive to the behavior type of the user. Being the poorest beneficiary, Farmer C benefits from the CEA rule. Since this farmer has the lowest demand, based on the CEA principle, his actual allocation is never less than his expectation as the cutbacks are normally borne by the richest farmer (Farmer A) and sometimes by Farmer B [36]. Overall, the performance of this rule is not robust and varies by the wealth level of the beneficiaries and their behavioral characteristics.[21] In comparison of CEA and proportional rules one cannot make a general conclusion about which rule can result in higher levels of benefits for users with certain behavioral types or users with certain wealth levels. This is due to the mixed effects of the CEA rule on the beneficiaries and social welfare. However, changing the conditions of the problem may alter this conclusion, so further studies are required to determine the conditions under which this rule outperforms the other in terms of benefit increase.

It must be noted that although the specifications of the groundwater example used here were arbitrary, this stylized benchmark problem has been designed such that it can reflect the different characteristics of the CPR problem and capture the effects of different initial conditions (e.g., wealth level, access level) on the overall results. The example is simple in that it involves only a few number of farmers, wells, and crop types. Nevertheless, the heterogeneity in the initial conditions of the cross-section model parameters (e.g., groundwater depth, farm size) and the variability of different conditions (e.g. groundwater depth, area under cultivation, pumping costs) during a 50-years modeling horizon make the major modeling results and their policy implications less sensitive to initial conditions.

[20] It is noteworthy that besides wealth level and behavioral characteristics, performance of this rule depends on the level of cutbacks. The tested cutback levels are within the near-optimal region and we do not expect that higher levels of cutback make this institution more effective in this numerical example. This is mainly because the robustness and social justice enforcement quality of this rule deteriorates for non-myopic users with increasing the cutback level.

[21] Similar to the case of proportional institution, based on the obtained results (Fig. 6d–f), higher levels of restriction are not expected to make this institution more effective. This is because the effectiveness of this institution based on the social justice and robustness criteria is worsened by increasing the restriction level.

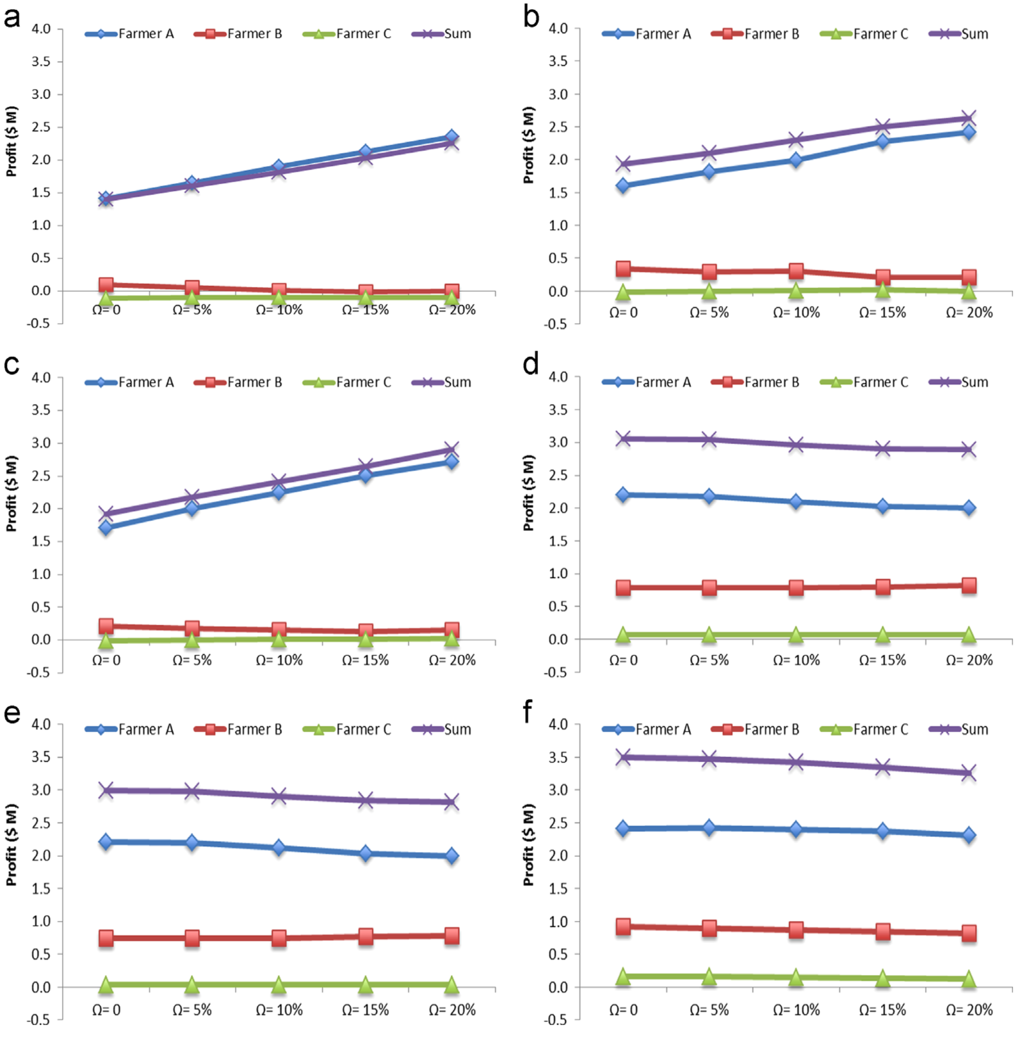

Fig. 6. CEA (bankruptcy) institution under different levels of intervention: total profits of farmers with different types of behaviors (a—Ignorant myopic management, b—Smart myopic management with drawdown penalty, c—Smart myopic management with profit penalty, d—Fixed ignorant non-myopic management, e—Variable ignorant non-myopic management, f—Smart non-myopic management).

5. Conclusions and policy implications

By focusing on CPR management through external regulatory interventions, this paper demonstrated how different exogenous regulatory institutions can affect the status of the CPR and the gains to its beneficiaries in the long run. Out of the analyzed institutions, namely the quota management, groundwater status management, tax-based management, and bankruptcy management institutions, the quota management and the status-based management institutions showed to be more effective based on three criteria: social welfare, social justice, and robustness. Without consideration of the possibility of tax returns (except for the case of withdrawal taxing), tax-based management, which resulted in decreased direct benefits from the CPR to the users in most cases, was found to be the worst type of external intervention. Nevertheless, similar to other institutions, the tax-based institution can be effective in reducing exploitation rates by the users to some extent. Moreover, in practice, the collected taxes can be re-distributed to the users to compensate for the revenue losses, or can be targeted for investment for increasing the efficiency of water extraction and use. Bankruptcy management institution is also effective in increasing the benefits to the users. However, its performance is not as desirable as the quota-based and status-based management institutions.

Groundwater quota management and status-based management institutions were found to be effective policy tools in prolonging the life of the CPR, increasing benefits to the users, and preventing a prisoner's dilemma, especially when users are short-term planners and ignore the externalities, typical of CPR users. The highest benefit to the users and zero drawdown of the resource are expected when total exploitation equals the recharge. Although highly restrictive quota management and status-based management policies may decrease the benefits to some users, restrictive policies are highly effective in securing sustainable CPRs when there is uncertainty about the users' behaviors and characteristics. Therefore, no matter how the beneficiaries develop their exploitation plans, highly restrictive quota management and state management policies can secure long-term benefits to the users. Beside dependency on the users' characteristics, the amount of benefits obtained by users under the quota management and status-based management institutions depends on the users' wealth level, with poorer beneficiaries gaining more from enforcement of these institutions than richer ones, suggesting that quota management and status-based management institutions are effective policy tools in enforcing social justice (transferring benefits from the rich to the poor). The actual benefits are more than the perceived ones for all types of farmers when they are highly restricted under these management institutions, resulting in a smaller difference between the actual and the perceived benefits of the farmers. Therefore, it is reasonable to conclude that the effects of ignorance of externalities and of short-foresight are minimized when stronger restrictions are enforced by the regulator.

Tax-based management institutions (e.g. electricity taxing, profit taxing, revenue taxing, and groundwater withdrawal taxing) fail to prolong the CPRs' life effectively. However, when monetary taxing methods are applied the collected funds may be used by the regulator for withdrawal monitoring and over-exploitation prevention. Here, it was assumed that exogenous regulatory institutions are enforced fully (with full obedience of the users). However, enforcing external interference is challenging and costly in practice. Therefore, one advantage of tax-based management over other external intervening institutions is generation of funds that can be used for enforcement of a tax-based institution. Also, collected taxes can be distributed among the users in different ways, resulting in some improvement in social welfare. In this study, only flat taxation strategies were tested which are not as effective as tiered taxation. Further studies should consider examining the effects of tiered taxing on the CPR's status and the beneficiaries' gains from it.

Proportional bankruptcy management institution is also another useful mechanism for prolonging the life of CPRs and increasing benefits to the users, if cut-backs do not result in over-reduction. In this study, however, this institution was not found to be as effective as quota management and state management institutions. This management institution was found to be more helpful to wealthier beneficiaries, making its performance questionable from the social justice standpoint. The Constrained Equal Award (CEA) bankruptcy management institution can be also effective in prolonging the CPR's life. However, this institution was found to be ineffective for non-myopic users (long-term planners). The performance of bankruptcy management institutions is highly dependent upon the users' types and wealth level. Therefore, these institutions are not necessarily appropriate when there is uncertainty about the users' characteristics. The proportional bankruptcy management outperformed the CEA bankruptcy management in effectiveness based on the social welfare, social justice, and robustness criteria. Therefore, although CEA bankruptcy management seeks assisting weaker users, proportional bankruptcy management seems to be more appropriate when long-term benefits of the weaker users is a point of concern, especially when the behavioral characteristics of the users are unknown.

This study only considered cases in which all beneficiaries showed the same behavior (had have the same characteristics or used the same non-cooperative management institution). Nevertheless, in practice, each CPR beneficiary may exhibit or adopt different types of management institutions, based on his preferences, knowledge, experience, foresight level, and other behavioral characteristics. Given that the users' choices of behavior and their resulting externalities might not be necessarily known by the regulator, robust policy making calls for selecting the exogenous regulatory institutions which are less sensitive to users' behavior, i.e. they can positively affect most types of users., Such exogenous regulatory institutions include quota-based or resource status-based management institutions. While it can be computationally challenging, future work should consider studying the situations in which users adopt a mix of CPR management institutions. This study also ignored the costs that may be associated with different regulatory interventions at various levels. Future studies may consider such costs to identify the optimal level of intervention under each exogenous regulatory institution.

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