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Methods

Non-cooperative institutions for sustainable common pool resource management: Application to groundwater

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ABSTRACT

As demands for limited natural resources increase, developing management institutions that ensure the sustainability of such resources is essential. Many natural resources are Common Pool Resources (CPRs), managed under different non-cooperative, cooperative, and externally imposed management frameworks. While early studies of non-cooperative CPR management suggest inevitable "tragedy of the commons," here we discuss how users can avoid tragic outcomes by changing their decision making rationales and exploitation strategies even in a non-cooperative environment. This paper introduces and compares various types of non-cooperative institutions that are available to manage CPRs. These management institutions are then applied, using a numerical groundwater exploitation example, to determine how different planning variables are affected by the choice of management institution. Results indicate that CPR users can improve their gains by considering the externalities and developing long-term exploitation plans, as opposed to short-term plans with no consideration of externalities that result in rapid exhaustion of the resource and lead to the so-called "tragedy of the commons."

1. Introduction

Many of the world's natural Common Pool Resources (CPRs) (e.g., groundwater, forests, pastures, and fisheries) face overuse and congestion due to increased competition for and the subtractability nature of their use. By focusing on current needs and short-term benefits, and ignoring the consumption externalities, users have exhausted many natural resources without considering the needs of future generations. Generally, CPRs share two important characteristics, namely nonexcludability and subtractability (Ostrom et al., 1994). Nonexcludability means that their size or characteristics make it costly, but not impossible, to exclude potential beneficiaries from obtaining benefits from their use. Subtractability means that they are rival (the benefits obtained by one beneficiary from the CPR reduces the available benefits from the CPR to other beneficiaries). Therefore, CPRs are not limited only to natural resources. They also include human-made resource systems, such as irrigation systems, public infrastructures, radio frequency spectra, etc. Similar to natural resources, many human-made resource systems face the problems of congestion or overuse, due to subtractability. The alarming outcomes of unsustainable resource management have raised the global concern about the impacts of increasing population and developing societies on CPRs, stimulating the growth in studying natural resource depletion, environmental degradation, and sustainable development, mainly over the last two decades (Arrow et al., 1996; Behrens et al., 2007; Callicott and Mumford, 1997; Dasgupta et al., 2000; Davis and Gartside, 2001; Dincer and Rosen, 1999; Gleick, 1998; Goodland, 1995; Hjorth and Bagheri, 2006; Loucks, 2000; Ludwig, 1993; Madani and Mariño, 2009; McMichael et al., 2003; Meadows et al., 2004; Munasinghe, 1999; Schaller, 1993). The growing body of studies has built a consensus among different disciplines, believing that a shift in the CPR management paradigm and changes in the CPR's governing policies and institutions are essential toward sustainability.

In early attempts to understand CPR problems, the negative outcomes of CPR exploitation in the presence of multiple beneficiaries (e.g., overuse, congestion, pollution, destruction, etc.) were associated with users' non-cooperative behavior and their choice of acting, based on individual rationality rather than group rationality. This resulted in the "tragedy of the commons" (Gordon, 1954; Hardin, 1968), which can be well explained within the Prisoner's Dilemma game structure, (e.g. see Madani (2010)), using the Nash non-cooperative solution concept (stability definition) (Nash, 1951). Therefore, traditional CPR research suggests enforcing external exploitation regulations and ownership rights to avoid negative outcomes and to overcome the CPR dilemma (Castillo and Saysel, 2005; Ostrom, 1990, 2010). More recent studies of CPR problems suggest that CPRs' future may be somewhat better than what was expected within the Prisoner's Dilemma structure. The main reason is that the beneficiaries may base their actions on group rationality (as opposed to individual rationality), develop cooperative CPR exploitation

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framework, and/or develop heuristic CPR management rules which are individual behavioral rules based on learning and past experience (Castillo and Saysel, 2005; McCarthy et al., 2001; Ostrom, 2010; Ostrom et al., 1994). Such suggested exploitation frameworks make the Nash non-cooperative solution concept inappropriate for justifying the CPR users' decisions (Fehr and Fischbacher, 2002; Madani and Hipel, 2011; Ostrom, 2010; Ostrom et al., 1994).

Three major categories of CPR governance framework can be recognized by reviewing the CPR literature:

Non-cooperative management institutions. Individual actions are common under these institutions. CPR beneficiaries may either adopt non-cooperative CPR management plans, which are based purely on individual rationality in which externalities are ignored, or develop heuristic CPR management plans, based on learning from past experience (Ostrom et al., 1994). Such heuristic behavior, while attempting to maximize individual benefits, considers also future outcomes and externalities and may contribute to the sustainability of the CPR as well. Our analysis in this paper allows identifying the effectiveness of various heuristic management plans.

Exogenous institutions. A regulator interferes by enforcing governing policies that regulate the exploitations (e.g., assigning exploitation rights, imposing maximum exploitation limits, taxation, etc.). The CPR beneficiaries react individually to the regulations. Cooperation among the CPR users is not expected under these institutions and increased benefits are obtained only when they obey the rules enforced by the higher authority. The analysis of exogenous institutions is dealt with in Madani and Dinar (2011a).

Cooperative management institutions. CPR users base their decisions on group rationality only and cooperate to minimize the externalities, prolong the CPR's life, and increase their gains. The analysis of cooperative institutions is dealt with in Madani and Dinar (2011b).

Selection of the optimal CPR management institution out of these three major categories is challenging, as each institution category has various advantages and disadvantages. While, typically, parties gain more under cooperative management institutions, the implication of cooperative schemes may be complicated in practice due to high transaction costs. Success of each management institution may depend on a variety of factors, including, but not limited to, size of the CPR, number of beneficiaries, trust level among the users, total demand imposed on the CPR, and wealth and education levels of the beneficiaries (Agrawal, 2003; Tang, 1991). Indeed, the optimal CPR governance framework is case-dependant. Thus, it is unreasonable to suggest one management institution category as the superior and optimal one, believing that it works best for any CPR, for any society of users, and under any situation.

Considering the value of each CPR management institution category and its suitability for a given CPR and group of users, an in-depth study of each category is essential to compare the range of options available under each institution to increase the efficiency of CPR management, leading to sustainable CPRs. This paper focuses on the first category of the introduced CPR governance institutions, namely the non-cooperative CPR management institutions. By introducing various non-cooperative management institutions and examining them, using a numerical example (a groundwater system), this paper recognizes different alternatives to increase the gains of CPR beneficiaries under non-cooperative arrangements, while preserving the CPR. The paper also derives useful CPR non-cooperative management lessons and discusses their policy implications.

2. Groundwater exploitation problem

Groundwater is one of the most studied types of CPRs (Blomquist, 1992; Gardner et al., 1997; Gisser and Sanchez, 1980; Provencher and Burt, 1993; Worthington et al., 1985). The complexity in estimating the externalities and monitoring exploitation when multiple groundwater users are present make the management of this CPR challenging. While to prevent overexploitation and to minimize the externalities, groundwater has been regulated to some extent in many areas, this resource is still facing overdraft, mostly due to complexity in enforcing the groundwater rights and monitoring groundwater withdrawal. In some other places groundwater is not yet regulated or is poorly regulated, requiring the users to manage it in using a non-cooperative or cooperative institution. Groundwater has been selected in this study as a sample CPR. By developing a numerical groundwater use example and formulating various non-cooperative groundwater decision models, it is shown how groundwater may be managed in a non-cooperative environment.

Groundwater has been treated in the various groundwater management studies, using either a command and control or cooperative approaches. This study extends the previous works by treating groundwater management in a non-cooperative manner and by applying mathematical formulations, which better reflect the groundwater behavior and the hydrogeologic characteristics of the problem, as well as the strategic nature of the user behavior. Below, we present the governing equations and main components of the groundwater decision-making model developed in this study.

2.1. Groundwater drawdown and response functions

The drawdown of groundwater level during time t at distance λ from the center of a well with a discharge rate of Q can be approximated, using the following equation (Loaiciga, 2004):

$$s = \frac{Q}{4\pi T}(a\cdot \ln t + b)\forall\lambda \tag{1}$$

where, given the distance λ, aquifer transmissivity (T) and storavity, coefficients a and b are estimated (Eq. (1) varies by λ) by regression of Eq. (1) against the predicted drawdown through the This equation for groundwater drawdown (Theis, 1935), resulting in a reasonable approximation of drawdown (Loaiciga, 2004).

When multiple (say n) wells tap water from the same aquifer, the drawdown in a given well (say well i) is not only affected by its own discharge, but also by the discharges of the n-1 wells around, each at distance λ_{ij} from well i. For such condition, Eq. (1) can be rewritten as (Loaiciga, 2004):

$$s_i = \frac{Q_i}{4\pi T}(a_{ii}\ln t + b_{ii}) + \sum_{\substack{j=1 \\ j\neq i}}^{n} \frac{Q_j}{4\pi T}\left(a_{ij}\ln t + b_{ij}\right)\forall\lambda_{ij} \tag{2}$$

where the first term in the right–hand side of Eq. (2) represents the drawdown caused by the ith well itself, and the second term represents the drawdown caused by the other $n-1$ wells around. In this equation, coefficients a_{ii}, b_{ii}, a_{ij} , and b_{ij} depend on the relative locations of other wells with respect to well i (λ_{ij}) (Loaiciga, 2004). This equation helps to better simulating cones of depression which occur in aquifers due to groundwater pumping. Based on this formulation, the level of drawdown over time is not the same in all wells pumping from the same aquifer. Application of this formulation makes the approach different from the "bathtub" approach in which the aquifer is considered as a large underground water reservoir with the same water level in all wells.

Eq. (2) clearly indicates that groundwater is a subtractable resource. So, any exploitation from the resource by one user, limits the available amount to others. In other words, pumping and lowering the water

[2] Negri (1989) distinguishes between a pumping cost externality and a strategic externality that arises from the competition among users to capture the groundwater reserves. Our model addresses the pumping cost externality only.

table at one well lowers the water level in other wells, as well.[2] Indeed, Eq. (2) is the key element for estimation of the externalities, if perfect information about the amounts of groundwater use at other pumps is at hand. Nonetheless, in practice, not only such information is not available (or reliable), but also estimation of actual drawdown is not easy for groundwater users, given the complexity of Eq. (2).

2.2. Cost functions

Energy is used for pumping groundwater. Thus, groundwater pumping has some costs to the users. The following equation can be used to estimate the groundwater pumping cost at a given well (modified from Loaiciga and Leipnik (2000)):

$$C_{Irr} = (us + v + d_{h-1})Q \tag{3}$$

where u and v are cost parameters, $d_{h\text{-}1}$ is the water depth in the well at the end of previous time step ($h-1$), Q is the total pumped volume (discharge), and s is the groundwater drawdown, resulting from Q (calculated based on Eqs. (1) or (2)).

Groundwater may be used by farmers who withdraw water for growing crops. A farmer who pumps groundwater for irrigated agriculture has to pay for irrigation water and other farming production costs (including harvesting costs, and irrigation facilities and well maintenance costs). The total cost to a farmer is:

$$C = C_{Irr,x} + C_{Tech} + C_{Other,x} \tag{4}$$

where C_{Tech} is a onetime initial investment for buying pumps and other irrigation technologies, represented by the annual-equivalent cost, and $C_{Other,\,x}$ (cost of seeds, fertilizer, planting, harvesting, etc.) assumed to be:

$$C_{Other,x} = i_x {l_x}^2 + j_x l_x + k_x \tag{5}$$

where l_x is the area under irrigation for growing crop x, and i_x, j_x, and k_x are cost parameters that depend on the crop type (x) (these parameters should be defined such that $C_{Other,\,x}\geq 0$ and $i_x<0$, $\frac{dC_{Other,x}}{dQ}\geq 0$).

2.3. Yield function

Assuming that the total crop yield is a function of the crop type (x), the area under irrigation for growing crop x (l_x), and the amount of water used for irrigation of crop x (Q_x), the total crop yield can be defined as:

$$Y_x = \left(p_x {l_x}^2 + q_x l_x\right) Q_x \tag{6}$$

where p and q are the parameters ($Y_x\geq 0$, $p_x<0$, and $\frac{dY_x}{dl_x}\geq 0$).

2.4. Profit function

The revenue, gained through selling the crop at the end of the growing season equals:

$$R = \sum_x z_x Y_x \tag{7}$$

where z_x is the price per weight unit of the crop x. Given Eqs. (4) and (7), the total profit of a farmer equals:

$$P = R - C \tag{8}$$

In planning for farming operations, each farmer needs to estimate the total present value of his profit over the planning horizon. The present value of the profit received in time step h equals:

$$P_p = Pe^{-rh} \tag{9}$$

where r is the time-step dependent discount rate. Given Eq. (9), the total present value of his profit over the planning horizon is:

$$Z = \int_0^H Pe^{-rh} dh \tag{10}$$

where H is the length of the planning horizon or the number of time steps (e.g., years) that the decision maker considers at the beginning of the planning horizon.

Normally, each farmer is willing to maximize his total profit over his planning period. However, within the CPR context, the status of the resource is affected by operations of all exploiters, which may fail to use the resource in an optimal and sustainable manner. Next, we will discuss how the objective function of the farmers may vary, depending on the non-cooperative operation institution they select.[3]

3. Non-cooperative groundwater management institutions

One important characteristic of most non-cooperative CPR management environments is the lack of perfect information on the part of each beneficiary about the decisions and plans of other beneficiaries. In such situations, users may benefit from speculations about plans of other users, based on their past experience and observations, to internalize the externalities in their planning. In a non-cooperative framework, each beneficiary may adopt different decision rules to determine the amount he wants to exploit from the CPR. The set of decision rules indicates that a beneficiary may range from being an ignorant decision maker, who totally ignores the externalities, to a smart decision maker, who learns from his past experience and continuously revises his exploitation plans. While the former type of decision making results in a big difference between the expected and actual gains from the CPR, the latter type can minimize the difference between his perceived and actual gains. In addition, heterogeneity in the decision maker's ability (e.g., due to his location, accessibility of the CPR, and other initial conditions) affects his ability to adjust and his expected utility level.

Below, we formulate the groundwater exploitation problem using a range of CPR management institutions for making decisions in non-cooperative situations. These institutions reflect the behavioral characteristics of the decision makers within a non-cooperative CPR management context.

3.1. Ignorant myopic management

Based on this institution, each farmer maximizes his expected profit (P_h) at a given time step, h, at the beginning of each time step, given the status of the CPR at h from his point of view (each farmer only considers the groundwater level in his own well). Mathematically, each farmer uses the following optimization model H times (for $h = 1, 2, \ldots, H$):

$$\text{Maximize} \quad P_{i,h} \tag{11}$$

subject to:

Eq. (1)
Eqs. (3)-(8)

where for farmer $i = 1, 2, \ldots, n$: $R_{i,\,h}$ is the farmer i's profit in time step h.

While at the beginning of each time step, decisions are made based on Eq. (1) without consideration of the effects of other farmers' exploitation rates (the externalities), at the end of each time step, the farmer finds the actual drawdown based on Eq. (2) and his actual profit. Using the latest information about the status of the CPR from his point of view (the water depth in the well under his operation), the farmer finds his optimal operation policies for the next period, and so on. The total

[3] We assume that all farmers apply the same management institution. Therefore, there is a public choice issue here that to be addressed. We refer to it in a later section.

gain of a farmer during the planning horizon (H) can be calculated using Eq. (10) and the realized profits, (with possible complete dissipated rents (Brooks et al., 1999; Gordon, 1954)) at the end of each step.

3.2. Smart myopic management

Farmers develop heuristic rules, based on their learning from the past in order to act non-myopically, when making short-term decisions. These rules help to minimize the difference between the expected profit and drawdown, based on Eq. (1), and the actual profit and drawdown, based on Eq. (2). To apply the heuristic rules, the farmers may revise the ignorant myopic management model by revising the objective function or constraints and/or by adding new constraints. As examples, two of these heuristic rules and their corresponding decision model's mathematical formulations are presented below. This is equivalent to some extent to the Pigouvian tax (Tietenberg and Lewis, 2008), levied, by a social planner, on a production process that creates negative externalities and aimed at internalizing individual externalities.

3.2.1. Smart myopic management with drawdown penalty

Over time, farmers learn that, as a result of pumping by other farmers, the actual drawdown (Eq. (2)) is normally more than what they predict at the beginning of that time-step (Eq. (1)). Therefore, they may impose a drawdown penalty to make their decision model less optimistic and to account for such possible differences. Nevertheless, in developing short-term plans, farmers make decisions for one time step only. In that case, the decision model can be formulated as:

Eq. (11)subject to:

$$s_{i,h} = \frac{Q_{i,h}}{4\pi T}(a \ln h + b) + \overline{sp_{i,h}} \tag{13}$$

$$\overline{sp_{i,1}} = 0 \ \ (\textit{initial condition}) \tag{14}$$

$$\overline{sp_{i,h}} = \frac{\sum_{t=1}^{h-1} sp_{i,t}}{h-1} \tag{15}$$

$$sp_{i,h} = s_{i,h-1\ :\ Eq2} - s_{i,h-1\ :\ Eq13} \tag{16}$$

Eqs. (3)–(8)

where for farmer $i = 1, 2, \ldots, n$: $\overline{sp_{i,h}}$ is the drawdown penalty for farmer i in time step h, equal to the average of drawdown penalties in the previous time steps; $sp_{i,\,h}$ is the drawdown penalty for farmer i at time step h; $s_{i,\,h-1:\,\mathrm{Eq}\ 2}$ is the actual drawdown in the previous time-step, calculated based on Eq. (2); and $s_{i,\,h-1:\,\mathrm{Eq}\ 13}$ is the expected (pre-estimated) drawdown in the previous time-step, calculated based on Eq. (13). At the end of each time step, the farmer finds the actual drawdown and his profit. The total gain of a farmer during the planning horizon (H) can be calculated using the actual profits, based on Eq. (10).

In this study, only a few different heuristic rules are presented. But, in practice, farmers do not always use the heuristic rules suggested here to reflect their learning and past experiences. They may develop many different forms of heuristic constraints to account for the externalities (van Steenbergen, No Date Provided). For example, in our management model, a more conservative (or pessimistic) farmer, who uses drawdown penalties in his decision model, may replace $s_{i,\,h-1:\,\mathrm{Eq}\ 13}$ in Eq. (16) with $s_{i,\,h-1:\,\mathrm{Eq}\ 1}$ and calculate the expected drawdown in the previous step using Eq. (1) (or the first term in Eq. (13)), resulting in higher drawdown penalties and more conservative decisions (this case is not considered in the present paper). Another example is a forgetful farmer with a short-term memory, who only considers the difference between the expected and actual drawdown in the previous time step, as opposed to the average of differences over the previous time steps. Such a farmer bases his decisions on his latest experience, resulting in less conservative decisions (this case is not considered in the present paper).

3.2.2. Smart myopic management with profit penalty

Instead of a drawdown penalty, farmers may use a profit penalty to account for the possible difference between their expected and actual gains. In that case, the farmers' decision model may be formulated as follows:

$$\textit{Maximize} \quad P_{i,h} - \overline{Pp_{i,h}} \tag{17}$$

subject to:

Eq. (1)
Eqs. (3)–(8)

$$\overline{Pp_{i,1}} = 0 \ \ (\textit{initial condition}) \tag{18}$$

$$\overline{Pp_{i,h}} = \frac{\sum_{t=1}^{h-1} Pp_{i,t}}{h-1} \quad (h = 2, 3, \ldots, H) \tag{19}$$

$$Pp_{i,h} = P_{i,h-1\ :\ Eq17} - P_{i,h-1\ :\ Eq2} \tag{20}$$

where for farmer $i = 1, 2, \ldots, n$: $\overline{Pp_{i,1}}$ is the profit penalty for farmer i in time step h equal to the average of profit penalties in the previous time steps; $Pp_{i,\,h}$ is the profit penalty for farmer i at time step h; $P_{i,\,h-1:\,\mathrm{Eq}\ 2}$ is the actual profit in the previous time-step, calculated based on the actual drawdown (Eq. (2)); and $P_{i,\,h-1:\,\mathrm{Eq}\ 17}$ is the expected profit in the previous time-step, calculated based on the expected drawdown in the previous step (Eq. (1)), using Eq. (17). At the end of each time step, the farmer finds his actual profit. The total gain of a farmer during the planning horizon (H) can be calculated using the actual profits and Eq. (10). An application of this management institution can be found in Kotchen and Salant (2009).

A more conservative (or pessimistic) farmer may replace $P_{i,\,h-1:\,\mathrm{Eq}\ 17}$ in Eq. (20) with $P_{i,\,h-1:\,\mathrm{Eq}\ 1}$ and calculate the expected drawdown in the previous step using Eqs. (1) and (8) (or the first term in Eq. (17)), resulting in higher profit penalties and more conservative decisions (this case is not considered in the present paper). For a less conservative and more forgetful farmer, the profit penalty may equal the difference between his actual and expected profits in the previous time step only (these cases are not considered in the present paper). The choice of the decision rule and heuristic decision model depends and a variety of factors including, but not limited to, behavioral characteristics of the decision maker, his trust level to other farmers, his first-hand experience and learning.

3.3. Fixed ignorant non-myopic management

Based on this institution, each farmer determines his optimal operation policies at the beginning of the planning horizon by maximizing his total present profit over the planning horizon without considering the effects imposed by other farmers on the status of the CPR from his point of view. Having a fixed management decision set (which includes decision variables such as pumping rate, drawdown, crop type, area under irrigation, etc.) is the important characteristic of this management institution. For the groundwater exploitation problem, farmer i ($i = 1, 2, \ldots, n$), who farms at farm i and pumps from well i, maximizes his total present profit (Z_i), using the following optimization model:

$$\textit{Maximize} \quad Z_i \tag{21}$$

subject to:

Eq. (1)
Eqs. (3)–(8)
Eq. (10)

where decision variables Q, s, x, l_x do not vary between time steps (as opposed to Q_h, s_h, x_h, $l_{x,h}$). A farmer, who makes his decisions based on this management institution, finds the selection of a fixed decision set to be more convenient than a variable decision set, especially in the absence of perfect information. Within this institution, the farmer ignores the imposed effects of other farmers (Eq. (2)). Therefore, his actual gained profit and operations will be different from the estimated profit and operations, using the above model. For instance, the actual drawdown, which will be higher than the predicted drawdown by each farmer (the actual drawdown can be determined by simultaneous solving of the above optimization model for all farmers), may make pumping uneconomical before the end of the planning horizon. An application of this management institutions is presented in Loaiciga (2004).

3.4. Variable ignorant non-myopic management

The general structure of the variable ignorant non-myopic management model is similar to the fixed ignorant non-myopic management model. However, under this management institution farmers use the above model with some modifications to find decision variables that vary between time steps (Q_h, s_h, x_h, $l_{x,h}$ as opposed to Q, s, x, l_x). A farmer who chooses a variable decision set believes that by changing his decisions between years, he can gain more and also prevent other farmers from having perfect information about his decisions.

3.5. Smart non-myopic management

A farmer who is smart (considers the externalities) and acts non-myopically (considers a long planning horizon) may adopt this management institution in a non-cooperative CPR environment with imperfect information. Based on this method, a farmer develops his long-term plan using the variable ignorant non-myopic decision model and starts exploiting the resource. At the end of the first time-step, since he learns his actual gains are different from what he had planned as a result of externalities, he develops another variable ignorant non-myopic plan, based on the latest status of the CPR from his point of view (depth of water in his well). The strong belief in long-term planning and consideration of the externalities motivates the farmers within this institution to develop and revise long-term plans. The continuous update of the long-term plan makes the farmers smart, although they develop ignorant plans at the beginning of each time step.

As an alternative, farmers may replace variable ignorant non-myopic plans with fixed ignorant non-myopic plans at the beginning of each time step (this case is not considered in the present paper).

4. Numerical example

We provide an illustrative example to demonstrate how the introduced non-cooperative groundwater management institutions can be applied in practice to develop various policy options. This example shows how choice of management institution can affect the status of the CPR and its beneficiaries in the long-run. The example includes three farmers ($i = A, B, C$) who tap the same aquifer (Fig. 1). Although, having only three farmers makes the problem somewhat simplistic, it allows capturing the basic characteristics of a CPR exploitation problem. Here, the three wells are benefiting from natural recharge,[4] which varies across the wells. Some recharge also results from the water use of each farmer on his land, as well as the water use of other farmers located at higher elevations. Thus, the net well discharge can be calculated as:

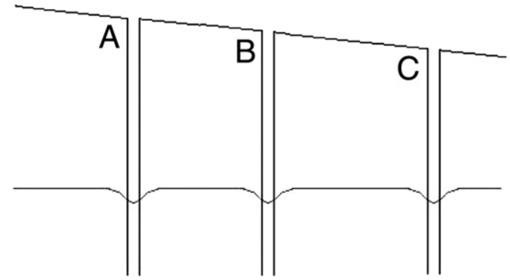

Fig. 1. Vertical cross section of the wells and aquifer at the beginning of planning horizon.

$$Q_{i,Net} = Q_i - \left(Q_{i,r} + \theta_i Q_i + \sum_{\substack{j=1 \\ j \neq i}}^{n} \omega_{i,j} Q_j \right) + Qe_i \tag{22}$$

where: Q_i is the amount of pumped discharge at the ith well; $Q_{i,\,r}$ is the natural recharge of the ith well; θ_i is the ratio of return flow to well i from water use on farm i; $\omega_{i,\,j}$ is the ratio of return flow to well i from water use on a nearby farm j; and Qe_i is the evaporative losses from well i. It is implicit that in calculating the drawdown (using Eqs. (1) and (2)) the net discharges should be used.

Tables 1[5] and 2 present the values of farmer-dependent and crop-dependent parameters used here, respectively. Here, the farmers, each operating only one well, are assumed to have two crop options (crop 1 and crop 2). The values of independent variables are $a = 9.125$, $b = 140$, $t = 365$ (given the values of other parameters, in this example, t should be set equal to 365 in Eqs. (1) and (2) to calculate the drawdown over one time–step (h), which represents one year), $T = 6{,}960\ m^2/day$, $u = 7.2\ \$\ m^{-3}/m^{-1}$, $v = 10\ \$\ m^{-3}$, and $r = 5\%/year$. It is also assumed that the farmers stick to the technology they are currently using. So, C_{Tech} is assumed to equal zero during the planning horizon. For simplicity, the evaporative losses from the wells are assumed to be minimal ($Qe_i = 0$). As shown in Fig. 1, the farms are located on land with some slope. Thus, the vertical pumping distances are not equal (the initial well's water depth is represented by d_0, given in Table 1).

5. Results

Since studying the long-term effects of different management policies on the CPR status is the focus of this study, the numerical example is solved using the suggested management institutions over a 50-year planning period ($H = 50$), which is considered to be reasonably long for the purposes of this study, considering the computational limitations. The groundwater quality issues are not considered in this study and can be the scope of future research.

Results of different model runs are presented in Figs. 2 to 5, indicating how some key variables of farmers' decision models change under different management institutions. Below, we discuss the modeling results under each management institution.

[4] For simplicity, the interrelated dynamics of groundwater and surface water are ignored here. However, groundwater recharge rates can be changed both by the natural conditions (e.g., climatic variations) as well as human impacts (e.g., rate of surface water withdrawal).

[5] While natural groundwater recharge rates ($Q_{i,\,r}$) are considered constant here, making the decision problem deterministic, in practice uncertainty about future climatic and other conditions and the resulting uncertainty about the natural recharge rate, can make the decision model more complex. Future studies may consider using stochastic decision models to address the uncertainty.

Table 1
Values of farmer-dependent parameters.

Farmer	Parameter												
	a_{iA}	a_{iB}	a_{iC}	b_{iA}	b_{iB}	b_{iC}	l (ha)	Q_r (m^3/year)	Θ	$\omega_{i,A}$	$\omega_{i,B}$	$\omega_{i,C}$	d_0 (m)
A	9.125	5.423	3.640	140	100	50	40	1,000	0.08	–	0	0	20
B	5.423	9.125	6.684	100	140	115	28	900	0.07	0.085	–	0	14
C	3.640	6.684	9.125	50	115	140	15	750	0.06	0.035	0.075	–	9

Table 2
Values of crop-dependent parameters.

Crop	Parameter					
	i (\$/ha^2/year)	j(\$/ha/ year)	k(\$/year)	p(Ton/m^3/ha^2/year)[a]	q(Ton/m^3/ha/year)	z(\$/ton)
1	-9.8175×10^{-3}	892.5	2.769	-2.49×10^{-10}	0.0256	150
2	-9.8485×10^{-3}	689.4	0.611	-7.51×10^{-11}	0.0280	134

[a] Ton per cubic meter of water per hectare of land per year. This is a measure for productivity of water applied.

5.1. Ignorant myopic management

Since the long-term effects of withdrawal policies are ignored under this management institution, farmers try to maximize their profit within each time step, with no future consideration. Therefore, the ignorant myopic decision makers start operations with an aggressive exploitation of the resource. As shown in Fig. 2a, the annual drawdown is greater in the beginning, and decreases over time as the growing water depth increases the pumping cost dramatically, putting some farmers out of business (Farmers B and C, as shown in Figs. 3a and 4a). Farmers with higher levels of wealth (i.e., Farmer A who owns a larger land area, resulting in lower costs and higher crop yield per unit area due to economies of scale (Eqs. (5) and (6)), can stay in business for a longer period of time than farmers with lower levels of wealth (i.e., Farmer C, who does not grow crops in one-third of the years). Therefore, the total groundwater withdrawal and drawdown over the planning horizon are higher for the wealthy farmers who benefit from their power during the implicit competition.[6] In this example, at the beginning of the period, Farmer A grows a higher-value crop (crop 1), which also has higher water demand and growing costs overall. As the groundwater depth and the resulting pumping costs increase, this farmer prefers to grow the lower-value crop (crop 2). Due to the high costs of growing crop 1 and the smaller farm size (diseconomics of scale) Farmer C never grows crop 1 during the 50-year period. Farmer B grows crop 1 only in the beginning of the planning period (6% of the years).

As shown in Figs. 2a and 3a, all farmers experience differences between their anticipated drawdown and profit at the beginning of each time step. They also experience differences between their actual drawdown and profit at the end of that time step, due to the unaccounted externalities. Over time, the difference gets smaller for all parties as they lower their withdrawals. The relative difference between the perceived and actual water depths and profits are the lowest for Farmer A, with the highest pumping rate (Figs. 2a, 3a, and 5a). Therefore, the amount of externalities that other farmers create for him is less than the amount he creates for other farmers. The opposite is true for Farmer C, with the lowest pumping rate (due to the lowest farm size, or wealth). The difference between the overall actual and perceived profits may range from 12% for Farmer A, to 258% for Farmer C, with the actual gain always less than the perceived gain, due to the unaccounted externalities (Fig. 5). Although, Farmer C pumps water from the well with the lowest depth to water table (the lowest pumping costs (Eq. (3)), and the highest recharge flows, due to the smallest farm size, he appears to be weakest in this competition, ending up with economic losses or negative profit (Fig. 3a) and the highest difference between the perceived and actual gains over the 50-year horizon (Fig. 5c). In this example Farmer B is the middle case between Farmers A and C (Fig. 5b), considering his farm size and vertical distance from the water table. The total gains of the farmers are lowest under the ignorant myopic management institution (Fig. 5d), making this management institution inferior to other possible non-cooperative management methods. Although changes in the discount rate result in changes in the overall gain of the farmers, their operation policies are insensitive to the discount rate as long as they are planning for short term.

5.2. Smart myopic management

In comparison with ignorant myopic management, both types of smart myopic management (with drawdown penalties (Figs. 2b and 3b) and with profit penalties (Figs. 2c and 3c)) are superior in terms of the overall profit to the farmers (Fig. 5) and the differences between the actual and perceived water depth (Fig. 2b and c), and profits (Fig. 3b and c). Comparison of Fig. 2a with Fig. 2b and c indicates that the annual drawdown trend does not vary significantly with changing the management institutions as long as the plans include short-term management institutions.

By acting smartly (considering the externalities), Farmer A can estimate his total gain over the 50-year period with 1% error. As a result of overestimating the penalties in some years (based on past experience), some farmers may end up with actual gain, that is higher than the perceived gain in those years (Fig. 3b and c). Despite overestimating the penalties in some years, Farmer C still suffers from overestimation of his annual profit and experiences negative profit overall. Nevertheless, this farmer can reduce his losses by acting smartly even with short-term planning. Over time, the difference between the actual and perceived drawdown and profit decreases, as a result of a decrease in total withdrawal (reduced externalities) and learning.

The farmers' choice of crop (Fig. 4b and c) does not change significantly by considering the externalities, using different types of penalties. That is not true for Farmer B, who does not grow crops in 50% of the years when he considers profit penalties, resulting in less drawdown and gain overall, compared to the case in which drawdown penalties are used. Planning with consideration of profit penalties is a better choice of management institution for Farmers A and C. Though, the sum of farmers' total gain in the 50-year period is larger when they consider drawdown penalties, as opposed to revenue penalties. The withdrawal policies are insensitive to the interest rate under this management institution, as the farmers plan for one time step at a time.

[6] This result has important policy implications with regards to impact of policy interventions on equity distribution, especially in developing countries (Seema et al., 2008).

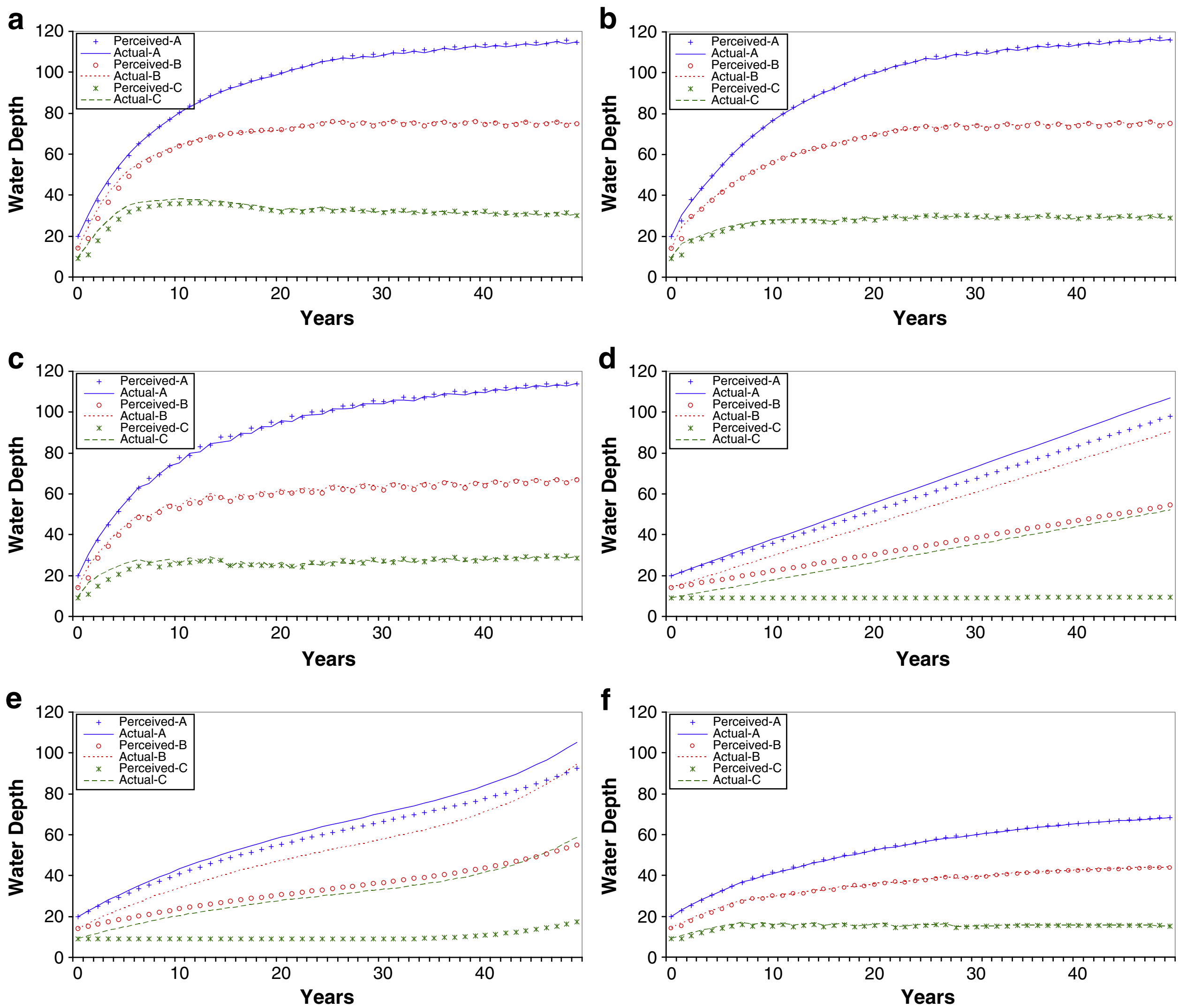

Fig. 2. Perceived and actual annual groundwater depth (in wells A, B, and C) under different non-cooperative management institutions (a — Ignorant myopic management, b — Smart myopic management with drawdown penalty, c — Smart myopic management with profit penalty, d — Fixed ignorant non-myopic management, e — Variable ignorant non-myopic management, f — Smart non-myopic management) over the planning horizon (50 years).

5.3. Fixed ignorant non-myopic management

Figs. 2d, 3d, and 5 show how farmers can increase their profit during their planning period by replacing short-term policies with long-term ones. Based on this management institution, farmers develop fixed decisions to maximize their profit over their planning horizon. Since each farmer's annual withdrawal and the resulting annual drawdown are constant, water depth (Fig. 2d) and pumping cost (Eq. (3)) increase linearly over time, resulting in a linear drop in the farmer's annual profit.

Although, more profit at the beginning of the planning period is preferred over more profit toward the end of the planning period (considering the non-zero discount rate), the farmers do not exhaust the resource entirely in the beginning. Farmers do not replace higher profit levels in the earlier years with no profit in later years, as a continuous exploitation of the resource is more profitable than a disrupted exploitation pattern. Nevertheless, by increasing the discount rate, the fixed exploitation rate increases, underlying the impact of interest rate on the withdrawal policies of groundwater users. Fig. 4d indicates that farmers grow crops in all years. When planning long term, to reduce the water depth and pumping costs in later time steps, farmers prefer to grow the low-value crop (crop 2) during the entire planning period, which has less water needs and also lower growing costs.

Based on the difference of the perceived water depth curves of the three farmers (Fig. 2d), one may conclude that wealthier farmers (with larger farm size) prefer to withdraw more from the resource, while farmers with lower levels of wealth prefer to withdraw less from the resource. To be able to use the resource in the long run, poorer farmers try to withdraw from the resource at a sustainable rate, using a fixed pumping rate over the planning horizon. In this example (Fig. 2d), Farmer C who has the lowest wealth level prefers to pump at the sustainable rate (withdraw equal to recharge). Therefore, the slope of his perceived drawdown curve is zero. This farmer prefers a continuous business with lower annual profits to an interrupted business, even if gaining higher profits in the beginning is possible. On the other hand, Farmers A and B, who are wealthier, pump more than the sustainable rate, with Farmer A (who has a larger farm) pumping at the higher rate. The rate of pumping is highly dependent on the length of the planning horizon. Here, a 50-year period has been selected as the planning horizon. Therefore, the optimization model seeks the most profit during this period with no consideration of future (beyond the 50-year limit). Therefore, the model suggests pumping at rates higher than the sustainable rate for Farmers A and B, who can stay in business during the whole planning horizon with such a pumping rate. If a longer planning horizon is

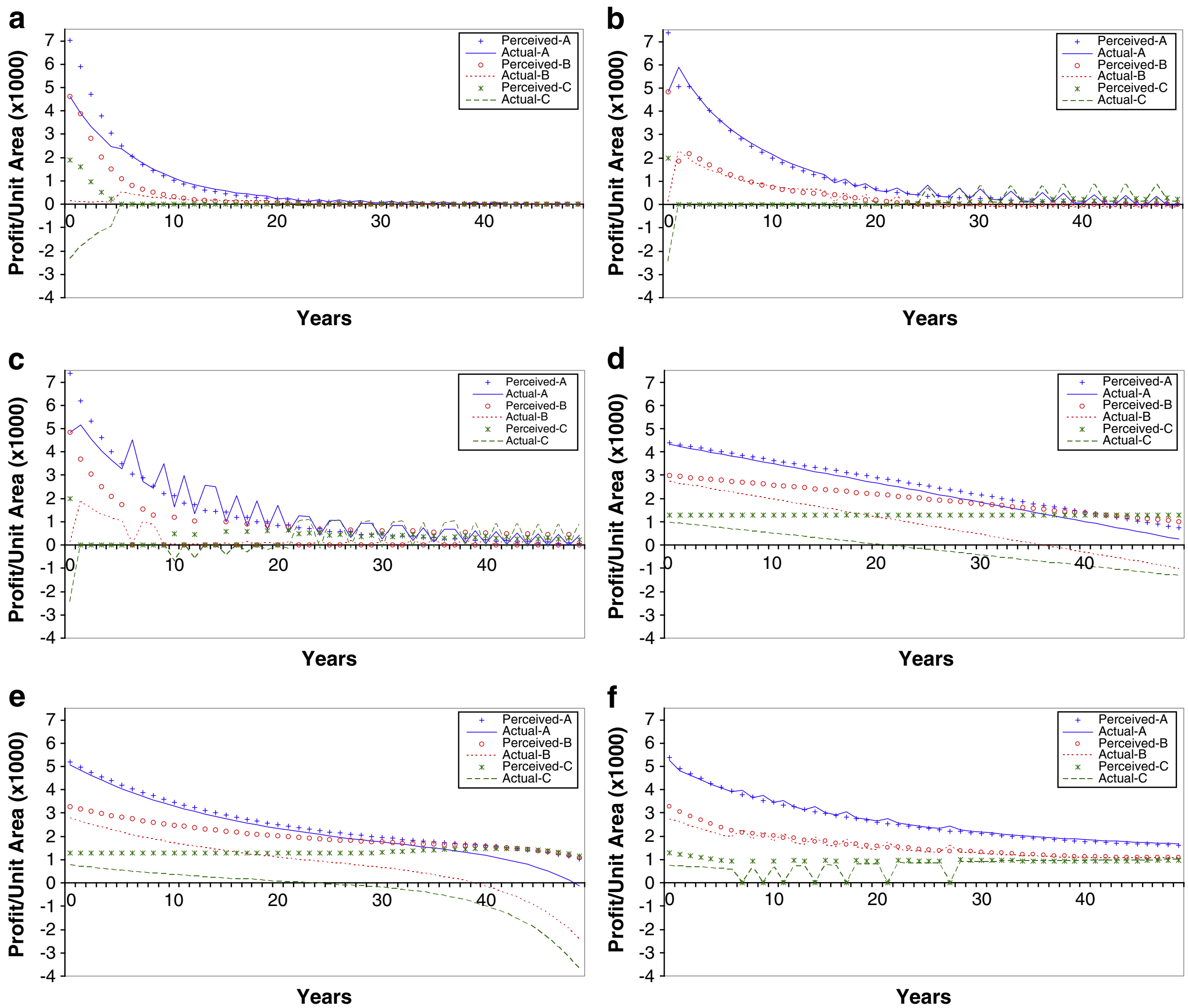

Fig. 3. Perceived and actual annual profit per unit land area (in $/ha) for farmers (A, B, and C) under different non-cooperative management institutions (a — Ignorant myopic management, b — Smart myopic management with drawdown penalty, c — Smart myopic management with profit penalty, d — Fixed ignorant non-myopic management, e — Variable ignorant non-myopic management, f — Smart non-myopic management) over the planning horizon (50 years).

considered, the decision model suggests lower fixed pumping rates for both farmers to ensure their continuous stay in business. By expanding the planning horizon, the farmers lower their fixed pumping rates until they reach a sustainable exploitation rate. In this example, the planning horizon, which requires a fixed sustainable pumping rate, is shorter for Farmer B than for Farmer A. For Farmer C, the 50-year planning horizon is long enough to force him to set his exploitation rate equal to the recharge rate.

The difference between the slopes of the actual and perceived water depth and profit curves of each farmer (Figs. 2d and 3d) indicates in relative terms how much that farmer is affected by the externalities. Based on this figure, one may conclude that the farmers with higher wealth levels, who can withdraw more from the resource, are less affected by the externalities. Therefore, the slope difference between the anticipated and actual drawdown or profit curves is lower for a farmer who withdraws more (Farmer A in this case) than for a farmer who withdraws less (Farmer C in this case).

Since farmers behave ignorantly and do not consider the externalities in their long-term plans, they underestimate the actual drawdown and profit (Figs. 2d and 3d). As a result of ignorant planning, Farmers B and C end up with losses in later years. Nonetheless, since the farmers plan for long term, their estimations are relatively better than their estimations based on different short-term planning options. Thus, the difference between the actual and perceived total profit is smaller when ignorant farmers plan for long term, compared with planning for short-term (Fig. 5), even if they are smart (consider the externalities). Also, the final water depth in each well and the total profit of each farmer decrease and increase respectively, when short-term planning is replaced with long-term planning.

5.4. Variable ignorant non-myopic management

Based on ignorant non-myopic plans with variable decisions, farmers increase their withdrawal over time, as shown in Fig. 2e. The lower pumping rates in the beginning of the period allow the farmers to stay in business in later time steps. Since farmers do not consider any point beyond the end of the planning horizon, their decision models suggest aggressive withdrawal and exhaustion of the resource in the last years of the planning horizon. Similar to the fixed ignorant non-myopic management, under this institution farmers grow the lower-value crop (Fig. 4e) to ensure a sustainable resource withdrawal and business. Since externalities are ignored under this institution (ignorant planning), with increasing the withdrawal, the difference between the perceived and actual drawdown curves of each farmer increases over time (Fig. 2e). The total drawdown in each well is less than the case in which short-term plans are developed, and not significantly different from the case in which fixed ignorant non-myopic exploitation policies are used.

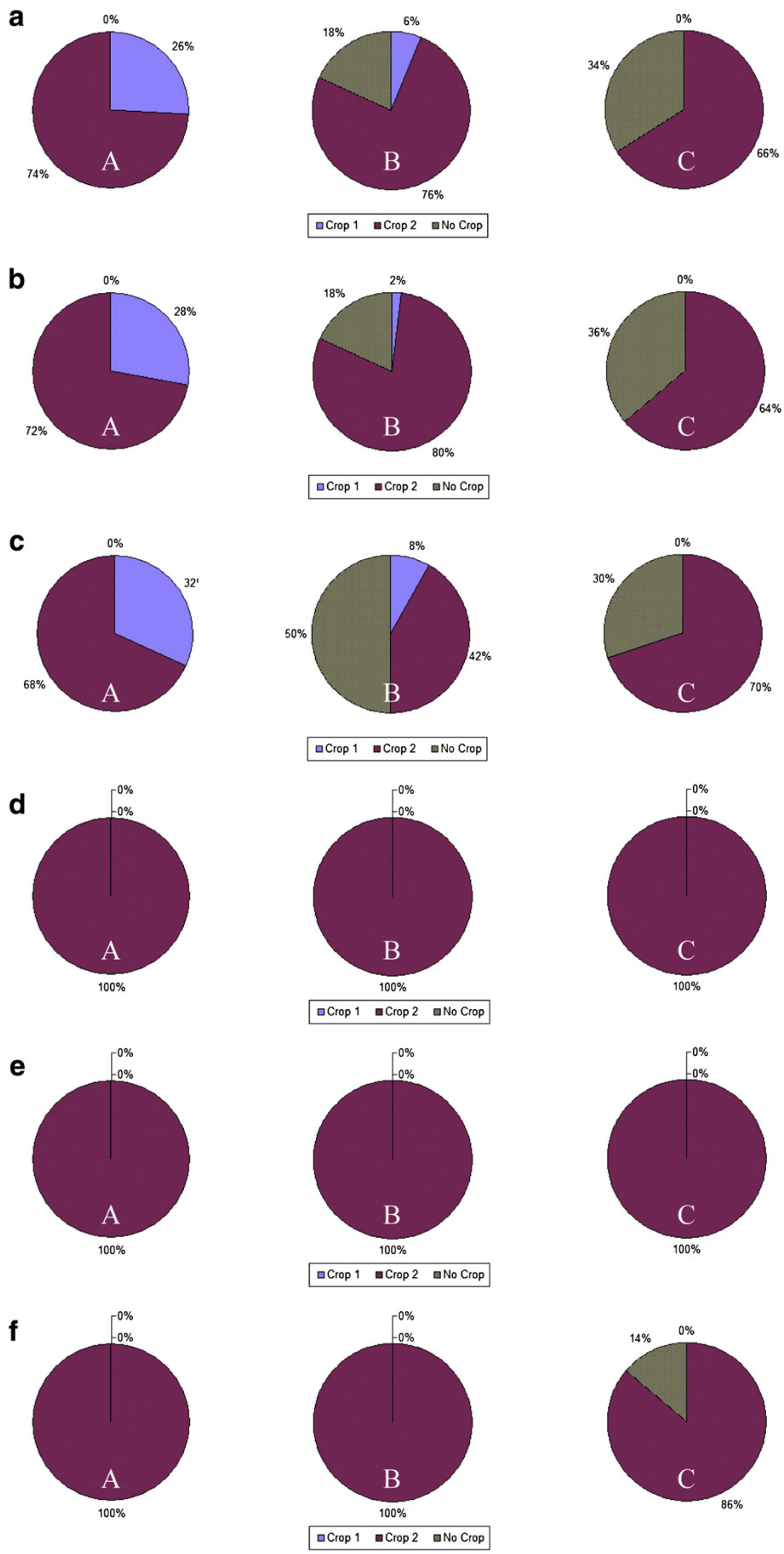

Fig. 4. Farmers' (A, B, and C) crop choice under different non-cooperative management institutions (a — Ignorant myopic management, b — Smart myopic management with draw-down penalty, c — Smart myopic management with profit penalty, d — Fixed ignorant non-myopic management, e — Variable ignorant non-myopic management, f — Smart non-myopic management) over the planning horizon (50 years).

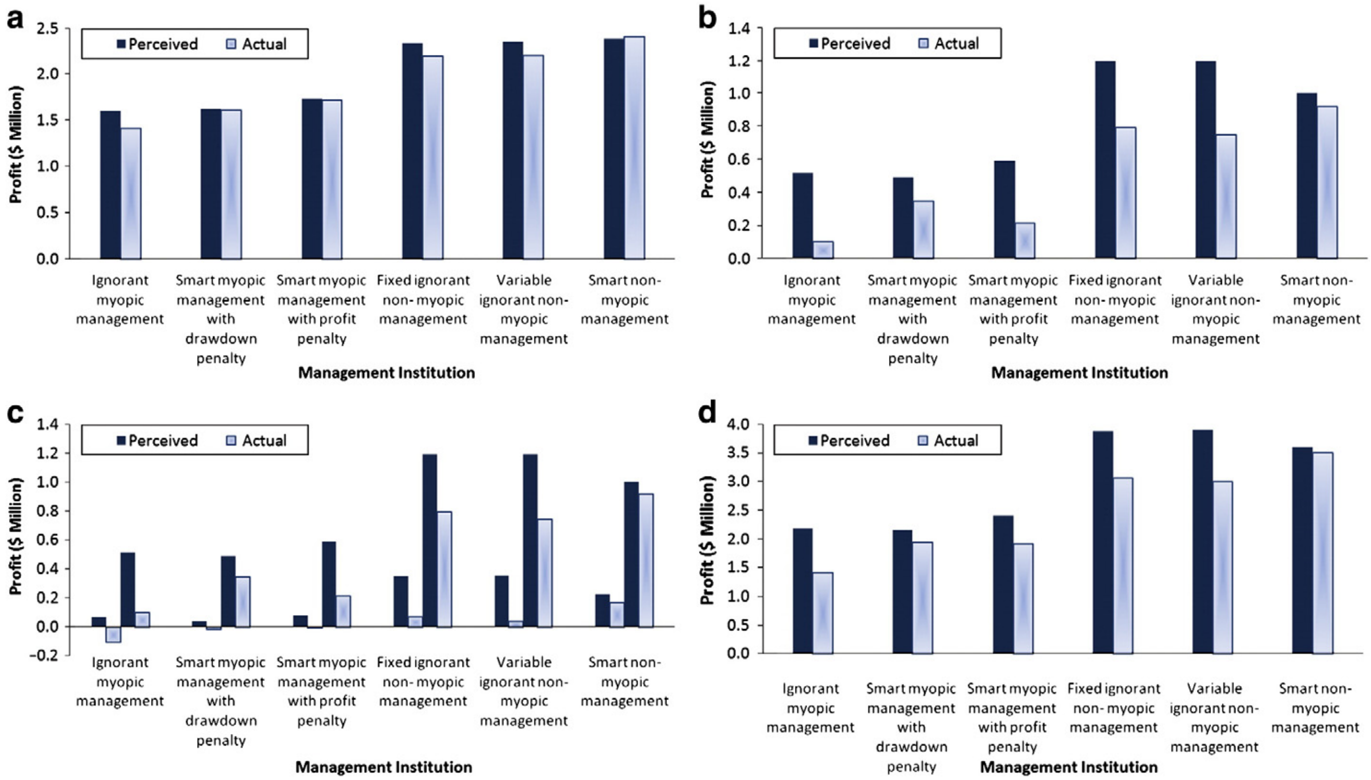

Fig. 5. Perceived and actual gains of the farmers (a — Farmer A, b — Farmer B, c — Farmer C, d — All farmers) under different non-cooperative management institutions over the 50-year planning horizon.

Similar to other management institutions, under the variable ignorant non-myopic management institution, farmers' revenue decreases over time with increasing pumping costs (Fig. 3e). As a result of ignorant planning, Farmers B and C incur negative profits toward the end of the planning horizon. While under this type of management institution, Farmer A's total gain is slightly more than his gain under the fixed ignorant non-myopic management institution (Fig. 5a), Farmers B and C gain less by replacing their fixed decisions with variable decisions in their long-term plans (Fig. 5b and c). The sum of the farmers' total gains under this management institution is higher than the sum of total gains under other management institutions, reviewed so far (Fig. 5d). An increase in the discount rate motivates the farmers to use the resource more aggressively in earlier years while a decrease in the discount rate has an opposite effect.

Comparison of Fig. 2d and e suggests that when variable decisions are allowed within a long-term exploitation plan, Farmer C deviates from the sustainable exploitation rate in the last decade of the planning horizon. This puts him in a worse position compared with the case in which fixed decisions are used in the long-term plan. Therefore, a planning horizon longer than 50 years is required for this farmer under this institution to converge his pumping to the sustainable rate. Similarly, the planning horizon that enforces sustainable exploitation by other farmers under this management institution is longer than the planning horizon under the fixed ignorant non-myopic management institution. The required length of the planning period increases with the wealth of the farmers.

Since the sum of the farmers' gains increases by replacing variable decisions with fixed decision in an ignorant non-myopic plan, one may conclude that the variable ignorant non-myopic management institution is inferior to the fixed ignorant non-myopic management institution. However, since the difference between the sums of the farmers' gains under the two management institutions is not significant, more study is required to derive such a conclusion with certainty. The difference between the exploitation rates under the fixed and variable ignorant non-myopic management institutions is expected to decrease by extending the planning horizon. If the planning horizon is long enough, both management institutions result in withdrawal at a sustainable rate over the entire planning horizon.

5.5. Smart non-myopic management

As shown in Fig. 2f, under this institution farmers' exploitation rates in the first years are similar to those under ignorant non-myopic management institution. But, since farmers plan smartly under this institution, they soon realize that in order to reduce the future costs, there is a need for reducing the withdrawal. Therefore, after the first few years, the slope of the water depth curves diminishes. As discussed, the slope of the water depth curve depends on the wealth level of the farmer. Here, Farmer C reaches the zero slope very soon. The other farmers need a longer planning horizon to equal their exploitation to the recharge rate. The continuous revision of the exploitation plan reduces the difference between the anticipated and actual resource level and profit, resulting in the best predictions by the decision makers among all different management institutions studied here (Fig. 5). Farmers A and B stay in the business during all years by growing the lower-value crop. Although, after few years Farmer C plans to exploit at the sustainable rate to keep the water depth at a constant level, the externalities imposed on this farmer force him to quit the business in some years and wait until the water depth gets higher through recharge. Although this farmer does not grow any crop in 30% of the years, his overall profit is higher now than in the other management institutions in which. In fact, under this type of management institution, this farmer never incurs any negative profit (true for other farmers, too) and he only grows crops when profitable. Therefore, even staying out of business for some years does not make his overall profit less than other cases in which he incurs profit losses. Similar to other long-term planning institutions, increase in interest rates can encourage more aggressive exploitation of the resource in earlier years.

The smart non-myopic management of the resource also results in the highest profit for all the CPR beneficiaries, making this management institution strictly superior to all other management options in this study.

6. Conclusions and policy implications

By focusing on non-cooperative CPR management, this paper demonstrated how different non-cooperative management institutions[7] can affect the status of the CPR and the gains of its beneficiaries in the long run. The ignorant myopic management is the worst type of management, which results in a rapid exhaustion of the resource and in the least profit to users, as suggested by "tragedy of the commons" literature. Nevertheless, results of our analysis indicates that even within a non-cooperative framework, parties can obtain less tragic outcomes and improve their gains by: 1) acting smartly and considering the externalities; and 2) acting non-myopically and developing long-term exploitation plans. Results show that long-term planning is more effective than ignorant short-term planning in increasing the gains to the CPR users. The best results were obtained under the smart non-myopic management institution, making this institution superior to all other options. Considering a very long planning horizon can result in a sustainable use of the resource.

Externalities and the lack of information about the decision of other CPR beneficiaries, which make the problem asymmetric in terms of information, may be addressed in exploitation plans through consideration of different penalties, based on learning and past experience.[8] The users' long-run benefits are highly sensitive to the length of the planning horizon. Results indicate that while both smart and non-myopic planners gain more than the ignorant short-term planner, the smart myopic planner gains less than an ignorant non-myopic planner. Therefore, long-term planning is more effective in improving the users' benefits than short-term planning with penalties. The maximum gain occurs under the smart non-myopic management in which externalities and long-term effects are considered simultaneously.

Through information, education, economic, and policy tools CPR users should be encouraged to consider the long-term effects of their actions on the CPR and the economic losses they may incur in the future by aggressive exhaustion of the resource in early stages. A user who considers a very long planning horizon will exploit at a sustainable rate. Therefore, the longer the planning horizon, the higher the overall profit. Due to learning and experience, CPR users deviate over time from the ignorant myopic planning and adopt institutions that can increase their overall gains. Therefore, in practice, outcomes are not as tragic and pessimistic as suggested by the "tragedy of the commons" theory. When external intervention is possible, various incentives (e.g., tax incentives for sustainable use of the resource) may be imposed to achieve better outcomes (than those predicted by "tragedy of the commons"). Educating the users about the destructive effects of short-term planning and ignoring the externalities through presentation of real world examples or experiments can be helpful in encouraging the users to deviate from ignorant myopic management institution. Real-time exploitation metering and continuous monitoring of the status of the CPR can be effective in encouraging the users to consider the externalities, when the obtained information is available to all.

Results also imply that the CPR users may change their exploitation strategy over time, not only as a result of learning, but also as a result of lower CPR levels. In our example, farmers reduced their groundwater withdrawals with time. Farmers will eventually set their exploitation rate equal to the recharge rate and pump at a sustainable exploitation rate. In case of renewable CPRs, natural limitations (e.g., lower groundwater levels) are eventually imposed on the users to prevent them from further exhaustion of the resource in an unsustainable manner. However, the natural limitations are not always desirable and, in some cases, CPRs may become unusable over a period before exploitation is resumed. For instance, groundwater over-pumping not only increases energy costs, but also can create land subsidence and water quality issues, which may make the resource unusable for some period. To avoid undesirable conditions caused by natural limitations as a result of unsustainable exploitation of the resource effective limiting policies (e.g. quotas, pumping curfew, and pumping technology) may be imposed on the users, when external intervention is possible.

The difference between the perceived and actual profit decreases as users get wealthier, suggesting that wealthier users are less vulnerable to the externalities, created by other users. This means they are less likely to respond to regulations, which is consistent with theory. When governments can interfere, different policy measures may be adopted to protect the poor users against wealthier users (e.g., imposing revenue taxes, removing electricity price subsidies for wealthier users).

While short-term exploitation plans are insensitive to the discount rate, high discount rates can motivate the long-term CPR exploitation planners to exhaust the resource more aggressively, as higher profits in early stages are more desirable to lower profits in the years to come. Therefore, an unstable economy can encourage unsustainable CPR exploitation by users with a long foresight level. On the other hand, in regions with stable economies with low-interest rates, these users benefit from trust to the future economic conditions and have incentives to develop long-term sustainable exploitation plans, supporting continuous business and profit.

The opposite slopes of the drawdown and revenue curves have an important policy implication, suggesting that rush for exhaustion of the resource results in a sharp drop in the gains of the parties. However, when the parties lower their exploitation rate, they can expect longer use of the resource (if renewable). The dominant strategy for a renewable CPR user is to set the slope of the drawdown curve equal to zero, which results in a revenue curve with the same slope, ensuring a sustainable use of the resource and benefit to the user. When all parties exploit at a sustainable rate, the externalities are minimal. Therefore, a sustainable resource extraction can be achieved even within a non-cooperative framework. But, in practice, the fear of other users using the resource at a rate higher than the sustainable withdrawal rate may result in a competitive behavior and deviation from sustainable exploitation. Communication, education, and governmental incentives can help create trust among the users and ensure sustainable CPR use within a non-cooperative management environment, which is often the case when a large group of users is involved.

The results presented in this study belong to cases in which all CPR beneficiaries use the same management institution. In practice users may adopt different types of management institutions, based on their preferences, knowledge, experience, foresight level, and behavioral characteristics. Future work may consider studying the situations in which a mix of management institutions is used by different CPR users.

[7] Estimation of the frequency of application of each type of the introduced non-cooperative management institution requires further research based on surveys as well as field and lab experiments. In fact, ignorant myopic management and smart non-myopic management institutions reflect two extreme cases of anti-ideal and ideal types of users, respectively. Based on the current conditions of the CPRs in practice, we can reasonably argue that most non-cooperative users have not been smart non-myopic planners. On the other hand, based on the gained experiences within the CPR management context all users have not been ignorant myopic planners. Therefore, it is reasonable to claim that most CPR users adopt the institutions which are in between the two extremes (e.g., smart myopic management and ignorant non-myopic management.)

[8] A similar result was obtained by Dinar and Xepapadeas (1998, 2002).

This study uses constant recharge rates, assuming the information about the recharge rates is available to all users. Therefore, the problem uses a simple deterministic optimization model. Since in practice, recharge rates may be variable due to different natural conditions and human impacts, CPR management problems involve uncertainty. Therefore, future studies may consider developing stochastic decision models to address the uncertainty.

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References

Agrawal, A., 2003. Sustainable governance of common-pool resources: context, methods, and politics. Annual Review of Anthropology 32, 243–262.
Arrow, K., Bolin, B., Costanza, R., Dasgupta, P., Folke, C., Holling, C.S., Jansson, B.O., Levin, S., Maler, K.G., Perrings, C., Pimentel, D., 1996. Economic growth, carrying capacity, and the environment. Ecological Applications 6, 13–15.
Behrens, A., Giljum, S., Kovanda, J., Niza, S., 2007. The material basis of the global economy Worldwide patterns of natural resource extraction and their implications for sustainable resource use policies. Ecological Economics 64, 444–453.
Blomquist, W.A., 1992. Dividing the waters: governing groundwater in Southern California. ICS Press. Distributed to the trade by National Book Network, San Francisco, Calif., Lanham, Md.
Brooks, R., Murray, M., Salant, S., Weise, J.C., 1999. When is the standard analysis of common property extraction under free access correct? A game-theoretic justification for non-game-theoretic analyses. Journal of Political Economy 107, 843–858.
Callicott, J.B., Mumford, K., 1997. Ecological sustainability as a conservation concept. Conservation Biology 11, 32–40.
Castillo, D., Saysel, A.K., 2005. Simulation of common pool resource field experiments: a behavioral model of collective action. Ecological Economics 55, 420–436.
Dasgupta, P., Levin, S., Lubchenco, J., 2000. Economic pathways to ecological sustainability. Bioscience 50, 339–345.
Davis, D., Gartside, D.F., 2001. Challenges for economic policy in sustainable management of marine natural resources. Ecological Economics 36, 223–236.
Dinar, A., Xepapadeas, A., 1998. Regulating water quantity and quality in irrigated agriculture. Environmental Management 54, 273–289.
Dinar, A., Xepapadeas, A., 2002. Regulating water quantity and quality in irrigated agriculture: learning by investing under asymmetric information environmental modeling and assessment, 7, pp. 17–27.
Dincer, I., Rosen, M.A., 1999. Energy, environment and sustainable development. Applied Energy 64, 427–440.
Fehr, E., Fischbacher, U., 2002. Why social preferences matter — the impact of non-selfish motives on competition, cooperation and incentives. The Economic Journal 112, C1–C33.
Gardner, R., Moore, M.R., Walker, J.M., 1997. Governing a groundwater commons: a strategic and laboratory analysis of western water law. Economic Inquiry 35, 218–234.
Gisser, M., Sanchez, S., 1980. Competition versus optimal control in groundwater pumping. Water Resources Research 16, 638–642.
Gleick, P.H., 1998. Water in crisis: paths to sustainable water use. Ecological Applications 8, 571–579.
Goodland, R., 1995. The concept of environmental sustainability. Annual Review of Ecology and Systematics 26, 1–24.
Gordon, H.S., 1954. The economic-theory of a common-property resource — the fishery. Journal of Political Economy 62, 124–142.
Hardin, G., 1968. Tragedy of commons. Science 162, 1243-&.
Hjorth, P., Bagheri, A., 2006. Navigating towards sustainable development: a system dynamics approach. Futures 38, 74–92.
Kotchen, M.J., Salant, S.W., 2009. A Free Lunch in the Commons. NBER Working Paper SeriesNational Bureau of Economic Research, Cambridge, MA.
Loaiciga, H.A., 2004. Analytic game — theoretic approach to ground-water extraction. Journal of Hydrology 297, 22–33.
Loaiciga, H.A., Leipnik, R.B., 2000. Closed-form solution for coastal aquifer management. Journal of Water Resources Planning and Management 126, 30–35.
Loucks, D.P., 2000. Sustainable water resources management. Water International 25, 3–10.
Ludwig, D., 1993. Environmental sustainability — magic, science, and religion in natural-resource management. Ecological Applications 3, 555–558.
Madani, K., 2010. Game theory and water resources. Journal of Hydrology 381, 225–238. doi:10.1016/j.jhydrol.2009.11.045.
Madani, K., Dinar A., 2011a. Exogenous regulatory institutions for sustainable management of common pool resources. Working Paper 01-0311, Water Science and Policy Center (WSPC), University of California, Riverside, available at: http://wspc.ucr.edu/working_papers/WSPC_WP_01-0311%20regulatory%20inst.pdf.
Madani, K., Dinar A., 2011b. Cooperative institutions for sustainable management of common pool resources. Working Paper 02-0311, Water Science and Policy Center (WSPC), University of California, Riverside, available at: http://wspc.ucr.edu/working_papers/WSPC_WP_02_0311%20coop%20inst%20com%20pool.pdf.
Madani, K., Hipel, K.W., 2011. Non-cooperative stability definitions for strategic analysis of generic water resources conflicts. Water Resources Management 25, 1949–1977. doi:10.1007/s11269-011-9783-4.
Madani, K., Mariño, M.A., 2009. System dynamics analysis for managing Iran's Zayandeh-Rud river basin. Water Resources Management 23, 2163–2187. doi:10.1007/s11269-008-9376-z.
McCarthy, N., Sadoulet, E., Janvry, A.d., 2001. Common pool resource appropriation under costly cooperation. Journal of Environmental Economics and Management 42, 297–309.
McMichael, A.J., Butler, C.D., Folke, C., 2003. New visions for addressing sustainability. Science 302, 1919–1920.
Meadows, D.H., Randers, J., Meadows, D.L., 2004. The Limits to Growth : The 30-Year Update. Chelsea Green Publishing Company, White River Junction, Vt.
Munasinghe, M., 1999. Is environmental degradation an inevitable consequence of economic growth: tunneling through the environmental Kuznets curve. Ecological Economics 29, 89–109.
Nash, J., 1951. Non-cooperative games. Annals of Mathematics 54, 286–295.
Negri, D., 1989. The common property aquifer as a differential game. Water Resources Research 25, 9–15.
Ostrom, E., 1990. Governing the Commons : The Evolution of Institutions For Collective Action. Cambridge University Press, Cambridge; New York.
Ostrom, E., 2010. Beyond markets and states: polycentric governance of complex economic systems. American Economic Review 100, 641–672.
Ostrom, E., Gardner, R., Walker, J., 1994. Rules, Games, and Common-Pool Resources. University of Michigan Press, Ann Arbor.
Provencher, B., Burt, O., 1993. The externalities associated with the common property exploitation of groundwater. Journal of Environmental Economics and Management 24, 139–158.
Schaller, N., 1993. The concept of agricultural sustainability. Agriculture, Ecosystems and Environment 46, 89–97.
Seema, H.M., Chandrakanth, M.G., Nagaraj, N., 2008. Equity In Distribution Of Benefits From-water Harvesting And Groundwater Recharge -An Economic Study In Sujala Watershed Project In Karnataka. Proceedings of the IWMI-TATA Water Policy Research Program, IWMI-TATA 7th Annual Partners' Meet, ICRISAT, Hyderabad, India, pp. 720–747.
Tang, S.Y., 1991. Institutional arrangements and the management of common-pool resources. Public Administration Review 51, 42–51.
Theis, C.V., 1935. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground water storage. EOS Transactions of the American Geophysical Union 16, 519–524.
Tietenberg, T., Lewis, L., 2008. Environmental & Natural Resource Economics, 8th Edition. Prentice Hall.
van Steenbergen, F., No Date Provided. Local groundwater regulation Water Praxis Documents 14, Land & Water Product Management Group, ARCADIS Euroconsult.
Worthington, V.E., Burt, O.R., Brustkern, R.L., 1985. Optimal management of a confined groundwater system. Journal of Environmental Economics and Management 12, 229–245.