Sustainable groundwater management with tradable permits

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Abstract

This article studies the sustainability of market-based instrument such as tradable permits for the management of a renewable aquifer used for agriculture production. In a dynamic hydro-economic model, a manager aims at satisfy different constraints in terms of food security and individual profit within a tradable permit scheme in the presence of myopic heterogeneous agents. We identify analytically the viability kernel that defines the states of the resource yielding inter-temporal feasible paths able to satisfy the set of constraints over time. We then illustrate the results with numerical simulations based on the data from Gisser and Sanchez (1980).

Keywords: Groundwater, Agriculture, Irrigation, Food security, Individual permits, Sustainability, Dynamic model, Viability kernel

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1. Introduction

Groundwater resources are under extreme pressure worldwide. About 20% of the world's aquifers are over-exploited (WWAP, 2015). Increasing demand for agricultural products to satisfy the needs of a growing population is the main driver behind water use together with drinking water. By 2050 agriculture will need to produce more than 60% of food as compared to the current situation (FAO, 2014). Irrigation is the principal user of aquifers and inefficient use of water for crop production depletes aquifers. As groundwater is a common property resource, aquifer depletion can occur when water extraction from myopic agents always exceeds its natural recharge. Regulation is needed to ensure a viable management of renewable aquifers and to sustain the exploitation of water resource.

The use of market-based instruments, such as transferable permits, has been proposed as a promising way to replenish an aquifer (Provencher, 1993) or to manage efficiently a groundwater aquifer for irrigated agriculture (Latinopoulos and Sartzetakis, 2015). Transferability ensures that water goes to the use with the higher value within the agriculture sector. The market price for permits is used as signal to allocate water between farmers. As farmers differ in their productivity but not in their extraction costs, economic efficiency implies that a more efficient farmer will produce more agricultural output with the same water amount than a less efficient farmer. In this context, efficiency also means that the amount of water extraction that a regulator allocates between farmers provides the maximum amount of food production. In a dynamic framework, combining surface and ground water, Knapp *et al* (2003) show that the aquifer management is efficient when water transfers are allowed between agriculture and urban sectors within a region as well as between regions. As pointed out by Roumasset and Wada (2012), there is a closed connection between groundwater and biological renewable resources, like fishs. The natural recharge rate is analogous to the biological growth rate for fish, except that the growth rate depends on the current stock while the natural recharge is exogenous. Water permits in aquifers are also analogous to individual and transferable quotas in fisheries (Branch, 2008; Chu, 2009; Pereau *et al*, 2012).

There has been considerable research in the development of hydro-economic model in the follow-up of the dynamic model of Gisser and Sanchez (1980). The state of art of this literature including management issues and game theoretical models has been adressed in Rubio and Casino (2001), Koundouri

(2004), Booker *et al* (2012), Madani and Dinar (2013) and Tomini (2014). In the design of a feasible water market, Ballestero *et al* (2002) suggest that the water reform will be more equitable and therefore politically acceptable if the allocation of permits is based on historical rights. It appears also important to ensure a minimum amount of profit to each farmer. But the main challenge remains to secure food supply for a large part of the population in many countries. This suggests a multi criteria approach to manage aquifers sustainably and to balance economic efficiency and equity. De Frutos Cachorro *et al* (2014) show that uncertainty on the natural recharge rate of an aquifer can create incentives for the water agency to more conservative extraction in the long run but also more intensive extraction in the short run. This suggests to define precautionary level of the resource along time in order to fullfilled some constraints and objectives.

This paper describes the management of an aquifer by a water agency using a transferable permit scheme facing myopic heterogenous farmers in the dynamic Gisser and Sanchez (1980) model. The analysis of our hydroeconomic model relies on the weak invariance (Aubin, 1990) or viable control method (Clarke *et al*, 1995). This approach focuses on identifying intertemporal feasible paths within a set of desirable objectives or constraints (Béné *et al*, 2001). This framework has been applied to renewable resources management and especially to the regulation of fisheries (Martinet *et al*, 2007; Doyen and Pereau, 2012), as well as to broader (eco)-system dynamics (Cissé *et al*, 2013). This method is used for the first time in groundwater management and is well-suited to analyse such issues.

The paper is structured as follows. Section 2 is devoted to the description of the dynamic hydro-economic model and the objectives of the water agency. Section 3 characterizes the feasible resource states and water policies under several constraints. An application illustrates the main results in Section 4. The last section concludes.

2. The hydro-economic model

2.1. The resource dynamics

An aquifer is described by its state variable (ie the height of water) $H(t) \in [0; S_L]$ at time t where S_L stands for the height of the ground surface. At $H(t) = 0$, the aquifer is empty, at $H(t) = S_L$ the aquifer is full. As described in Figure (1) the height of water increases with constant rainfalls $R > 0$ and decreases because of extraction $W(t)$ dedicated to agriculture by n farmers with $W(t) = \sum_{i=1}^{n} w_i(t)$. We suppose that a proportion μ of the water used for irrigation comes back to the aquifer. Then total extraction is $(1-\mu)\,W$ where $0 < \mu < 1$ stands for the non-absorption coefficient.

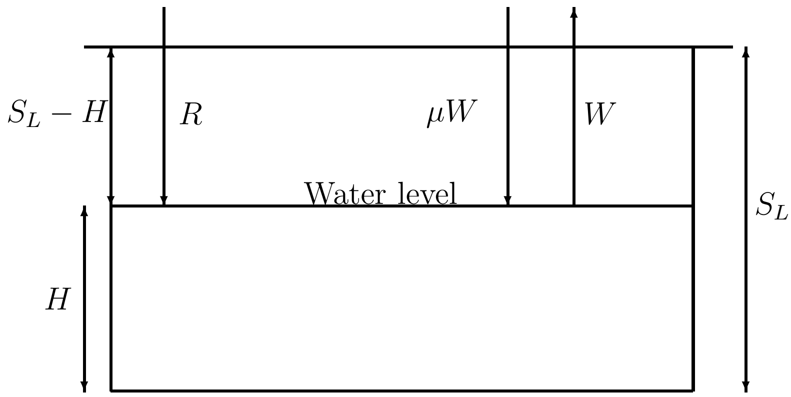


Figure 1: Description of an aquifer

Based on Gisser-Sanchez (1980), the dynamics of the resource is

$$\begin{aligned} H(t+1) &= H(t) + \frac{R}{AS} - \frac{(1-\mu)}{AS} W(t) \\ H(0) &= H_0 \end{aligned} \tag{1}$$

with A stands for the area of the aquifer and S the storage coefficient.

Eq (1) can be rewritten as

$$H(t+1) = H(t) + \frac{1-\mu}{AS}\,(W_R - W(t)) \tag{2}$$

where $W_R = \frac{R}{1-\mu}$ stands for the groundwater use that would keep the height of the water table constant $(H(t+1) = H(t))$. If the extraction is too high $(W(t) > W_R)$, the rainfalls are not enough to compensate the extraction and the aquifer empties.

2.2. The water permit market

A set of n heterogeneous farmers use water denoted by w_i from the aquifer for their agricultural activity. The individual profit of a farmer i is given by

$$\pi_i(t) = p_y y_i(t) - c(t) w_i(t) - m(t)\left(w_i(t) - w_i^-(t)\right) \tag{3}$$

The first term of (3) refers to the total revenue with p_y the price of the agricultural product and $y_i(t)$ the individual production which is assumed to be a quadratic form of the water use $w_i(t)$

$$y_i(t) = a_i w_i(t) - \frac{b_i}{2} w_i^2(t) \tag{4}$$

where $a_i, b_i > 0$ are technical parameters of production. Marginal productivity is positive and decreasing. Individual production reaches a maximum for $\overline{w_i} = a_i/b_i$ yielding $\overline{y_i} = a_i^2/2b_i = a_i\overline{w_i}/2$. It implies that individual water extraction $w_i \in [0, \overline{w_i}]$. The maximum amount of water consumption is $\overline{W} = \sum_{i=1}^{n} \overline{w_i}$ and the maximum amount of production is then $\overline{Y} = \sum_{i=1}^{n} \overline{y_i}$. Farmers are supposed to be price takers on the product market.

The second term of (3) refers to the extraction cost. The unitary cost $c(t)$ is given by

$$\begin{aligned} c(t) &= c_1(S_L - H(t)) \\ &= c_0 - c_1 H(t) \end{aligned} \tag{5}$$

where $c_0 = c_1 S_L$ stands for a fixed cost and c_1 is the marginal pumping cost. The unitary cost increases when the level of the water table decreases. When the height of the water table is at its maximum, the unitary cost is nil (Rubio and Casino, 2001).

The third term of (3) refers to the transferable permit market where $m(t)$ stands for the unitary price of the water permit. It is assumed water extraction is managed by a regulator who allocates transferable water permits to the n farmers at the beginning of each period t. After receiving their water entitlements $w_i^-(t)$ free of charge at each period, farmers decide whether to buy or sell water permits to other farmers and how many to trade, based on their annual water uses $w_i(t)$. It is assumed that water permits are not transferable through time, that is, no banking or borrowing of water permits is allowed.

The total water supply (ie the global amount of water allocated by the regulator) is computed as follow

$$W(t) = \sum_{i=1}^{n} w_i^-(t) \tag{6}$$

The aggregated water quota demand is depending on the optimal individual quotas, which emerges from the maximisation of individual profits

$$\max_{w_i} \pi_i(t) \tag{7}$$

First order conditions give

$$w_i^*(t) = \left(\frac{a_i}{b_i} - \frac{c_0}{p_y b_i} - \frac{m(t)}{p_y b_i}\right) + \frac{c_1}{p_y b_i} H(t) \tag{8}$$

We can check that $w_i^* \in [0, \overline{w_i}]$. We deduce the aggregate water demand

$$W^*(t) = \sum_{i=1}^{n} w_i^*(t) = \overline{W} - \beta \frac{c_0}{p_y} - \beta \frac{m(t)}{p_y} + \beta \frac{c_1}{p_y} H(t) \tag{9}$$

with

$$\overline{W} = \sum_{i=1}^{n} \frac{a_i}{b_i}; \beta = \sum_{i=1}^{n} \frac{1}{b_i} \tag{10}$$

The clearing market condition on the water market implies equality between water supply and demand

$$W(t) = \overline{W} - \beta \frac{c_0}{p_y} - \beta \frac{m(t)}{p_y} + \beta \frac{c_1}{p_y} H(t) \tag{11}$$

We deduce the equilibrium water price $m^*(t)$

$$m^*(W(t), H(t)) = \frac{p_y}{\beta} (\overline{W} - W(t)) - c_0 + c_1 H(t) \tag{12}$$

This expression confirms the economic intuitions with $\frac{\partial m^*}{\partial W} < 0$ and $\frac{\partial m^*}{\partial H} > 0$. An increase in the water supply faced to an unchanged demand implies a decrease in the water price. When the height of the water table is high, water extraction increases and thus the demand of permits, pushing up the water price.

3. The regulator constraints

3.1. The tradable water permit constraint

If a positive permit demand exist, then the price of the water permit $m^*(t)$ is positive

$$0 \leq m^*(W(t), H(t)) \tag{13}$$

This positivity condition on $m^*(t)$ yields a state-control constraint

$$W(t) \leq \left(\overline{W} - \frac{\beta c_0}{p_y}\right) + \frac{c_1 \beta}{p_y} H(t) \tag{14}$$

By denoting the above function by W^m, it implies

$$W(t) \leq W^m(H(t)) \tag{15}$$

The tradable water permit constraint entails a higher limit on the value of the total water extraction $W(t)$. This superior bound is an increasing function of the state variable $H(t)$). This bound depends on the economic parameters of farmers.

3.2. The food security constraint

To deal with the questions related to food security, the aggregate production of the agricultural sector has to satisfy a minimum threshold:

$$Y_{lim} \leq Y^*(t) \tag{16}$$

with the aggregated production $Y^*(t) = \sum_{i=1}^{n} y_i^*(t)$

By substituting m^* (eqn. 12) within w_i^* (eqn. 8)

$$w_i^*(t) = \frac{1}{b_i}\left(a_i - \left(\frac{\overline{W} - W(t)}{\beta}\right)\right) \tag{17}$$

and thus the optimal individual productions becomes

$$y_i^*(t) = \frac{1}{2b_i}\left(a_i^2 - \left(\frac{\overline{W} - W(t)}{\beta}\right)^2\right) \tag{18}$$

Taking the sum of (18) yields the aggregated production

$$Y^*(t) = \sum_{i=1}^{n} \frac{a_i^2}{2b_i} - \frac{1}{2}\left(\frac{\overline{W} - W(t)}{\beta}\right)^2 \sum_{i=1}^{n} \frac{1}{b_i} = \overline{Y} - \frac{1}{2\beta}\left(\overline{W} - W(t)\right)^2 \tag{19}$$

with $\overline{Y} = \sum_{i=1}^{n} \overline{y_i}$.

The aggregated production constraint $Y_{lim} \leq Y^*(t)$ bounds the water supply $W(t)$ to an inferior limit W_{FS} such that

$$W_{FS} \leq W(t) \tag{20}$$

where W_{FS} is constant and independent from the state variable:

$$W_{FS} = \overline{W} - \sqrt{2\beta\left(\overline{Y} - Y_{\text{lim}}\right)} \tag{21}$$

We can check that $W_{FS} \geq 0$ for $Y_{\text{lim}} \geq \overline{Y} - \left(\overline{W}^2/2\beta\right)$.

4. Theoretical results

4.1. The viability kernel

The dynamics of the aquifer given by (1) is taken into account in combination with

1. the water permit price constraint (15): $W(t) \leq W^m(H(t))$
2. the food security constraint (20): $W_{FS} \leq W(t)$

In an infinite horizon context, the viability kernel can be defined as the set of initial situation H_0 such as it exists water extraction $W(t)$ and resources $H(t)$, satisfying the previous constraints, for any time between $t = 0, 1, ...T$.

We obtain the following proposition:

Proposition 1. *Assume that $Y_{lim} < \overline{Y}$, we obtain*

- *If $W_{FS} > W_R$ then no viability occurs $Viab = \emptyset$*
- *If $W_{FS} \leq W_R$ the viability kernel is $Viab = [H_{\lim}, +\infty[$*

where $H_{\lim}$ is the resource threshold which emerges from the intersection of the three constraints.

Proof: Consider the dynamics

$$H(t+1) = H(t) + \frac{1-\mu}{AS}(W_R - W(t))$$

with $W_R = \frac{R}{1-\mu}$.

We first show that $W_{FS} \leq W_R$ implies $Viab = [H_{\lim}, +\infty[$.
Assume that $H_0 \geq H_{\lim}$, choose $W = W_{FS}$ then

$$H + \frac{1-\mu}{AS}(W_R - W) = H + \frac{1-\mu}{AS}(W_R - W_{FS}) \geq H \geq H_{\lim}$$

Hence $[H_{\lim}, +\infty[$ is viable and $Viab = [H_{\lim}, +\infty[$.

Now if $W_{FS} > W_R$, we show by forward induction that

$$\begin{aligned}
H(1) &= H(0) - \left(\frac{1-\mu}{AS}\right)(W_{FS} - W_R)) \\
H(2) &= H(0) - 2\left(\frac{1-\mu}{AS}\right)(W_{FS} - W_R)) \\
H(t) &= H(0) - t\left(\frac{1-\mu}{AS}\right)(W_{FS} - W_R))
\end{aligned}$$

Hence $\exists t^*$ such that $H(t^*) < H_{\lim}$, it implies that $Viab = \emptyset$

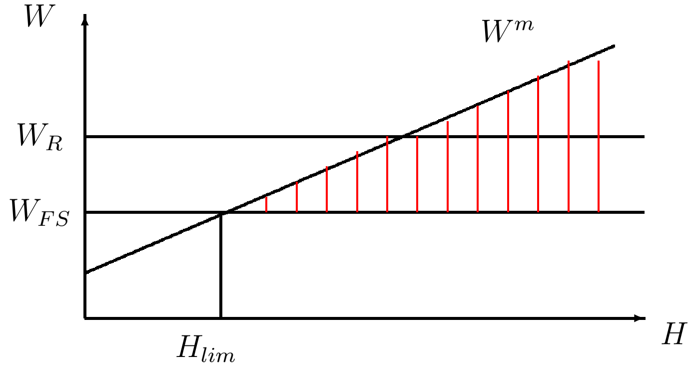


Figure 2: Viable case.

4.1.1. The resource threshold

Combining the transferable water permit constraint (15) and the food security constraint (20) gives

$$W_{FS} \leq W(t) \leq W^m(H(t)) \tag{22}$$

This yields a constraint on the level of the water table

$$H_{\lim} \leq H(t) \tag{23}$$

where $H_{\lim}$ emerges from the intersection of the different constraints.

More precisely, we define $H_{\lim}$ the threshold on H due to the intersection of the water permit constraint (15) and the food security constraint (20)

$$H_{lim} = \frac{c_0}{c_1} - \frac{p_y}{c_1\beta}\sqrt{2\beta\left(\overline{Y} - Y_{\lim}\right)} \tag{24}$$

It turns out that $H_{\lim} \geq 0$ for $Y_{\lim} \geq \overline{Y} - \frac{\beta}{2}\left(\frac{c_0}{p_y}\right)^2$.

4.1.2. The water quota constraint

The resource threshold $H_{\lim}$ has to be verified within a dynamic context $H_{\lim} \leq H(t+1)$. Using eq (1), we obtain

$$W(t) \leq W_R + \frac{AS}{(1-\mu)}\left(H(t) - H_{\lim}\right) \tag{25}$$

Denoting by W^+ the above function, the dynamic context of the resource threshold yields

$$W(t) \leq W^+(H(t)) \tag{26}$$

This dynamic constraint leads to a superior bound for the total water extraction $W(t)$. This superior limit is an affine and increasing function of the state variable $H(t)$. The function $W^+(H(t))$ is characterized by (H_{lim}, W_R). In other words, we can define a limit case: when $H(t) = H_{\text{lim}}$, the dynamic constraint becomes $W(t) \leq W_R$. This limit case imposes a constraint on the food security constraint. Indeed, being able to satisfy simultaneously the food security constraint $W_{FS} \leq W(t)$ and the dynamic constraint at the limit case $W(t) \leq W_R$ requires $W_{FS} \leq W_R$. If the food security is too demanding, the water extraction requiring for the demanding production is at each time higher than the rainfalls. The water table decreases towards 0, it is not possible to define any viable extraction.

To show under which conditions the dynamic constraint is binding, we consider the limit case $H(t) = H_{\text{lim}}$. For that value, the two functions W^m and W^+ intercept $W_{FS} = W_R$ at H_{lim}. Il implies that W^+ will be below W^m for $H \geq H_{\text{lim}}$ when the slope of W^+ is lower that the slope of W^m. It implies the following condition on the marginal pumping cost

$$c_1 > \left(\frac{AS}{(1-\mu)}\right)\left(\frac{p_y}{\beta}\right) \tag{27}$$

When $W_{FS} \leq W_R$, the condition on the slope implying by eq (27) need also to be satisfied. We can show this implies that the intercept of W^+ with the $y - axis$ is higher than W_{FS}:

$$H_{\text{lim}} > \frac{1-\mu}{AS}(W_R - W_{FS})$$

4.1.3. The highest food security bound

To go further, we can specify the condition $W_{FS} \leq W_R$ with the parameters of the food security constraint. The condition $W_{FS} \leq W_R$ becomes

$$Y_{lim} \leq \overline{Y} - \frac{(\overline{W} - W_R)^2}{2\beta} \tag{28}$$

It implies a maximum value for Y_{lim} denoted by Y_{lim}^{max}

In other words, the condition $W_R \leq W_{FS}$ bounds the values of Y_{lim} for which the viability kernel is not empty. We can note that in the limit case

$W_{FS} = W_R$, the threshold value $H_{\lim}$ is equal to the water steady state value obtained by Gisser and sanchez (1980) with identical myopic agents.

Proposition 2. *The maximum aggregate production is obtained when* $Y_{lim} = Y_{lim}^{max} < \overline{Y}$. *For that value the food security constraint is binding by the groundwater recharge that keep constant the height of the water table,* $W_R = W_{FS}$.

It turns out that combining the minimum amount of agricultural production derived from the food security constraint and the above maximum value yields the following condition which is always satisfied under $\overline{W} \geq W_R$)

$$\overline{Y} - \frac{(\overline{W})^2}{2\beta} \leq Y_{lim} \leq \overline{Y} - \frac{(\overline{W} - W_R)^2}{2\beta}$$

4.2. The viable quotas

We are able to specify the viable quotas W associated to the viable water tables.

Proposition 3. *Considering that* $W_{FS} \leq W_R$, *the viable quotas associated to* $Viab = [H_{\lim}, S_L]$ *are*

$$W^{Viab} = \left[W_{FS}, min(W^m(H), W^+(H))\right]$$

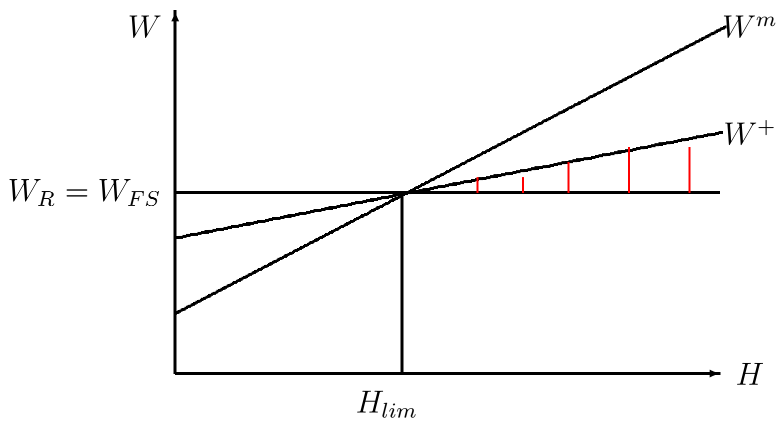


Figure 3: Viable water quotas when $W_{FS} = W_R$

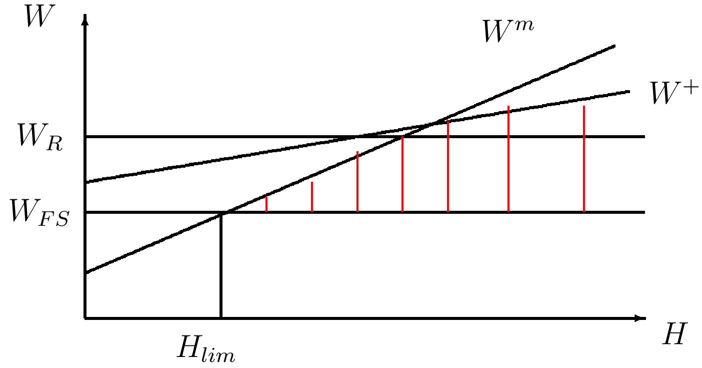


Figure 4: Viable water quotas when $W_{FS} \leq W_R$

5. Numerical simulations

5.1. The case of study

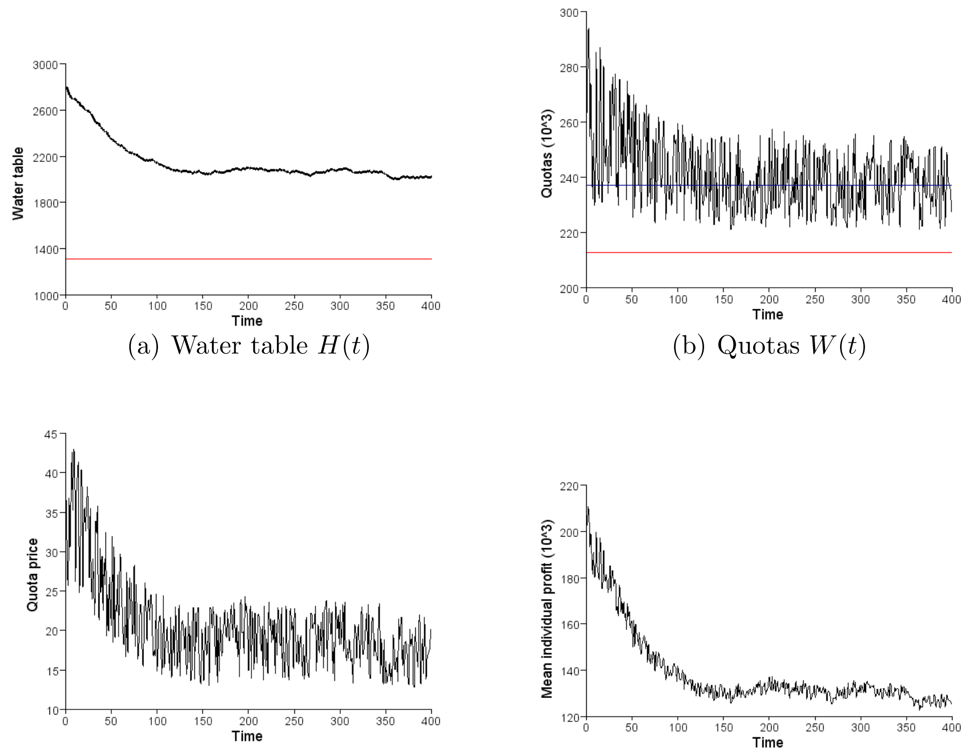
The numerical example is based on the case study of Gisser and Sanchez (1980) adapted to deal with heterogeneous farmers.

Parameters	Description	units	value
μ	Return flow coefficient	Unitless	0.27
R	Natural recharge	ac ft/yr	173000
AS	Aquifer area times storativity	ac ft/yr	1500
c_0	fixed cost	\$/ac ft	125
c_1	Pumping costs	\$/ac ft per foot of lift	0.035
H_0	Initial water table elevation	feet above sea level	2800
a_i	production coefficient	\$/ac ft	96.218676
b_i	squared production coefficient	\$/ac ft	0.0204562
n	number of farmers	Unitless	100
p_y	crop price	\$/ac ft	1.5

Gisser and Sanchez (1980) specified an aggregate linear water demand $W = g - kp_w$ with $g, k > 0$ and p_w the water price. By identification with our model and assuming with identical players, we have $g = n\,(a/b)$ and $k = n/bp_y$. Using the values of a, b, n and p_y gives the value of GS $g = 470365$ and $k = 3259$. Heterogeneity between the farmers is introduced through the values of a_i and b_i. Compared to GS case study, we also choose a lower value of AS and H_0 to reduce the simulation horizon.

5.2. The viability domains

Figure shows an example of viability domain based on the numerical example.



(a) Water table $H(t)$

(b) Quotas $W(t)$

(c) Price quota $m(t)$

(d) Mean profit $\sum_n \frac{\pi_i(t)}{n}$

Figure 5: Trajectories of the water table $H(t)$, the quotas $W(t)$, the price quota $m(t)$ and the mean individual profit $\sum_n \frac{\pi_i(t)}{n}$. In figure (a), the red line stands for the H_{lim}. In figure (b), the red line stands for the food security constraint W_{FS} and the blue line represents W_R.

6. Conclusion

7. Acknowledgements

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8. Appendix

To obtain the specification adopted by Feinerman and Knapp (1983), consider the new state variable $Z(t) = S_L - H(t)$ measuring the pumping lifts. Eq (1) can be rewritten as

$$Z(t+1) = Z(t) - \frac{1-\mu}{AS}\left(W_R - W(t)\right)$$

while the unitary cost is

$$c(t) = c_1 Z(t)$$

where c_1 stands for the cost of energy needed to lift one acre-foot of water. The food security constraint W_{FS} (20) remains unchanged and the tradable water permit constraint (15) become

$$W(t) \leq W^m(Z(t)) = \overline{W} - \frac{\beta c_1}{p_y} Z(t)$$

The state threshold Z_{lim} is

$$Z_{\text{lim}} = \frac{p_y}{\beta c_1}\sqrt{2\beta\left(\overline{Y} - Y_{\text{lim}}\right)}$$

The water quota constraint $W^+(Z(t))$ implies

$$W(t) \geq W^+(Z(t)) = W_R - \frac{AS}{1-\mu}\left(Z(t) - Z_{\text{lim}}\right)$$

When $Z(t) = Z_{\text{lim}}$, W^m and W^+ intercept $W_{FS} = W_R$ at Z_{lim}. Condition (27) is unchanged.

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