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Can Nonlinear Water Pricing Help to Mitigate Drought Effects in Temperate Countries?

Jean-Philippe Terreaux and Mabel Tidball

Abstract

The notion of drought is most often associated with the aridity of landscapes and vegetation. But a green landscape can hide a frequent imbalance between water availability and the quantity necessary to maintain rivers in a suitable state, to satisfy different water needs. This is the case, for example, in the French region called New Aquitaine. Regularly, "drought" crisis committees are set up there to limit water use through administrative constraints, which is technically difficult and costly for many, and with an overall unsatisfactory situation from rural areas to the coast. But in summer, water consumption is mainly due to irrigation. Some water resource managers have consequently set up an original non-linear water pricing system for irrigation to achieve several objectives: above all, to limit water consumption in order to respect a minimum flow rate in rivers, to anticipate water supply-demand imbalances before agricultural plantations are made, to allocate water to the users who value it best, to recover water supply costs, to be transparent and sufficiently simple in its application to be acceptable. In this chapter, we propose to describe one of such original pricing systems, as well as some of its main mathematical properties and its practical interests.

Keywords: drought, irrigation, nonlinear pricing, environment, mathematical economics

1. The problem of chronic droughts in France

Economic and trade developments and the growth of the world's population are leading to an increasing exploitation of natural resources. In addition, this global evolution is accompanied by changes in the economic, social, and environmental context (climate change and spread of species becoming invasive), making more uncertain the context in which different professions work. For example, the farmers now face a multiplicity of new climatic, market, and biotic risks. In this context, the implementation of measures to secure various resources, including water, helps to mitigate the negative effects of these developments. More generally, various tools to combat hazards have been put in place at the individual level: insurance or other risk pooling systems, diversification, etc.

But with regard to water resources, even in some areas where they were once considered abundant, the limits of their exploitation may have been reached. And because property rights over these resources are often poorly established,

the “tragedy of the commons” (see [1]) is repeated. For example, in the agricultural sector, everyone is encouraged to make the most of available water in their own interest, while well-designed coordination of the different uses would improve everyone’s well-being or economic performance (see, for example, [2]).

The problems thus created have repercussions on the agricultural activity itself, which can no longer rely on a sufficient supply of water, and on the community in general: on the environmental level (e.g., river dewatering), on the economic level (impact on downstream sectors, such as shellfish farming or tourism, as the European Coastal project shows, see [3]), or on the social level with farmers quite often being accused of many wrongdoings. This is also one of the reasons for the implementation at European Union level of the Water Framework Directive (see e.g., [4]).

Thus, a green landscape such as those frequent in the French region of New Aquitaine can hide recurrent problems of drought, with very frequent crises in areas such as the Charente “département.” As a result, the public authorities regularly intervene, imposing different constraints to farmers or to their Water User Associations (WUA) in charge of the resource management (e.g., restrictions on irrigation, while crops are in place) to allocate the water shortage. The situation is then penalizing for everyone, and especially for farmers, who too often cannot adequately grow the crops in which they have invested. And it ultimately leads to a perfectible situation on each of the three pillars of a sustainable development: economic, social, and environmental.

This situation is well documented and explained in game theory, particularly in the context of the “prisoner’s dilemma” (see [5]). But it gives few solutions, except to seek coordination between stakeholders. The “tragedy of the commons” can generally be resolved by privatizing the resource, but in France and in many countries, this solution cannot be applied to the water resource for legal reasons (see, for example, [6] for their developments on this subject). This is what opponents of water storage in reservoirs remind us, arguing that the resource must benefit all uses and that it cannot be used by a single sector of the economy.

On the other hand, at some short distance from this Charente département, and still in the New Aquitaine Region, an original attempt at water pricing has been made in order to try to better coordinate farmers’ actions, by anticipating as well as possible the annual imbalances between water supply and demand. The objective is thus to make the best use of public information (the water level in rivers, groundwater or reservoirs, climatic conditions, market conditions, etc.) and also private information (importance for farmers of securing their water supply, linked, for example, to their product sales contracts, their debt level, or more simply their risk aversion), but without being inquisitorial (by making them reveal only what is important for the water resource management). Of course, this does not guarantee that there will be no crisis, but it does make it possible to anticipate them as well as possible and to resolve a majority of possible conflicts well before the plots are planted, that is, before the distribution of the shortage has any serious consequences. This too gives the farmers the possibility to change their culture choices in order to adapt them more precisely to the available water.

The idea, developed by the irrigators of the Compagnie d’Aménagement des Eaux des Deux-Sèvres (CAEDS), is to base the price of irrigation water paid each year on two variables: the quantity of water reserved by each farmer (before planting) and the quantity actually consumed. We show here that the pricing formula used encourages the farmer to subscribe a quantity directly related to what he expects to consume (which makes it possible to deduce very quickly what each farmer plans to consume and the total consumption, which makes it easier, as we saw, to resolve possible conflicts, as well as consequently to respect more easily the

minimum flow rates in the nearby rivers). Finally, we show that it is possible to modify the volumes consumed globally by varying the parameters.

In a way, by creating value not only from the water resources but also simultaneously from public and private information, this makes it easier to resolve conflicts of use, by reducing the frequency of crises. This approach combines mechanism design, game theory, and nonlinear pricing results.

In the rest of this chapter, we give a very short overview of some of the literature on irrigation water resource pricing (see [7] for some aspects), as well as on nonlinear pricing (see [8]). Then we develop a mathematical model to show different properties of this pricing formula and in particular why volume subscription by farmers makes it possible to anticipate their consumption.

2. Literature review: agricultural water economics and nonlinear pricing

In France, after having built many individual or collective dams in order to increase water-storage capacity (“supply management”), efforts are currently focused on “demand management,” that is, the use of less irrigation water for the same production and the search for more efficient alternatives for sharing water among the different uses while trying to find more efficient water pricing schemes (see [9]). The problem is similar in other parts of the world (see, e.g., [10] for China).

The aims of water management are multiple and may sometimes be understood as contradictory ([11]): the first one is to allocate water to users who valorize it at the best (efficiency). The second is to guarantee an access to this essential good to everybody and to be acceptable in order to be applied (equity). Moreover, as mentioned in [12], it may be a tool to redistribute public investment benefits. The third is to recover costs induced by water extraction/distribution/use. The fourth is to be transparent and simple enough to be understandable, and it is clear that a two variable tariff, as the one presented here, is quite acceptable as shown by the fact that it was implemented in the CAEDS area. Another nonlinear pricing scheme is also established in the Compagnie d’Aménagement des Coteaux de Gascogne area in the southwest of France and is compared in [13] and [14] to the one presented here as regards the agricultural production, the farmers revenue, and the water quantity used for irrigation in accordance with the climatic conditions.

Generally speaking, water pricing practices can be classified in two families: volumetric and non-volumetric methods. Volumetric methods rely on the volume and require metered water facility (see [15] or [16], for examples of the implementation of a volumetric pricing system). Non-volumetric methods are based on output/input other than water, for example, in the agricultural sector as per area pricing (see [17]). The last methods are widespread because of their simplicity, but they do not encourage saving water.

When using volumetric methods, water can be priced in three main ways. The price can be either constant whatever the level of consumed water or defined “per block”: the cost per additional consumed unit varies when the consumption reaches some given thresholds. The marginal pricing can either increase with the level of consumption (increasing block tariff) or decrease (declining block rate). The application of such a pricing is studied for domestic water use, for example, in [18].

The increasing block tariffs (IBT) can be used to impose conservation incentives on some target group of large users. Customers facing the higher prices at the margin will, in theory, use less water than they would under the uniform pricing; customers facing lower prices at the margin will use more. The expectation is that

demand in the high blocks will be more elastic than demand in the low blocks, resulting in a net decrease in water use when compared to a uniform pricing. Although there is widespread consensus that IBT have many advantages, this type of tariff still deserves more careful examination since an incorrect structure of the IBTs leads to several shortcomings as argued in [19]. Some of them are difficulties to set the initial block; mismatch between prices and marginal costs; conflict between revenue sufficiency and economic efficiency; absence of simplicity, transparency, and implementation; incapacity of solving shared connections; etc.

The decreasing block tariff (DBT) is, unlike the preceding one, in accordance with the proposition that high-value goods “should” be bought at higher price than low-value goods. Water will be first purchased for uses with high values and then only for uses which will lead to less welfare increases. Concerning equity, this type of tariff is “not advisable”. “The consumers who acquire smaller amounts of the good and/or service because of their low incomes would be bearing a higher price than those who can afford to consume greater amounts” (see [20]). But it can be justified in the following circumstances:

- When users have very different levels of consumption. A consumer hundred times bigger than the average consumer does not create costs hundred times higher, because there is only one pipe line, one billing process, etc. And, since cost per volume is lower with large consumers, it is justifiable to propose DBT in the case of heterogeneous users.
- In order to incite users to stay in the WUA: as we have explained above, IBT (e.g., see [21]) might encourage users who have access to alternative water sources to quit (partly at least) the network, stopping to contribute to the recovery of the costs. This can lead to cost recovery problems for the water supplier and besides might lead to negative environmental consequences. DBT does not have this negative incentive.

A two-part tariff combines a fixed and a volumetric rate (or a mix of fixed and variable elements). “Under this system, consumers must pay an entry charge that entitles them to consume the good. Subsequently they will pay an additional smaller amount for each extra unit consumed.” “Two-part tariff is easy to explain and easy to understand” is mentioned in [20]. But in practice, it fails to reach the efficiency objective and suffer from the fact that it does not allow to reveal information on water demand, which may be at the origin of sudden discrepancy between water supply and demand.

In the following sections, we study the properties of a different pricing structure, in which farmers make a water reservation (e.g., during wet period or before planting) and then pay a water bill which is an increasing function of water reservation and of real water consumption (e.g., during dry period or during peak vegetation). This allows the WUA manager to forecast disequilibrium between water demand and supply. The water pricing is parameterized, in order to adapt the price to the actual WUA situation and to the available water supply.

3. The model

3.1 Notations

We consider a WUA composed of n farmers and which provides them irrigation water at a cost. Each farmer i has a production function we note $h_i(C_i)$ which is a

function of the volume C_i of the water he consumes. This production function is private information, known only by the farmer himself.

Each year, each farmer firstly reserves a water volume S_i , for example, before choosing his planting and then consumes another volume C_i for the field irrigation, C_i being either inferior or superior to S_i . The pricing formula is designed in order to take into account these two variables and to display some properties.

The notations we use are the following:

- B is the total water user association expenses.
- D is proportional to B : $D = \lambda B$, with a constant $\lambda > 0$.
- S_i is the volume reserved by agent i during the considered year.
- C_i is the volume consumed by agent i during the same year.
- $h_i(C_i)$ is agent i 's production function, which depends on the consumed water C_i .
- $F = F(S_i, C_i)$ is the sum agent i must pay (his water bill).

For each agent i , the pricing formula is

$$F(S_i, C_i) = D \left(aS_i + (1 - a) \frac{C_i \max(C_i, bS_i)}{S_i} \right) \quad (1)$$

with $a \in [0, 1]$ and $b \in [0, 1]$.

The pricing scheme is a common knowledge for all farmers and is the same for all of them. Parameter a represents a kind of sharing of the price between, on the first hand, the reservation part and, on the other hand, the consumption part. As $D = \lambda B$, the role of parameter λ is to ensure a balanced budget, under the financial conditions of the WUA, for example, by adjusting the value of this parameter by trial and error year after year, if a temporary budget imbalance is permissible. We will return to this point in Section 3.3, examining in particular the case where a minimum of revenue each year is required. The role of parameter b is to incite to reserve at least the forecasted consumption divided by b . For a S_i given, when $C_i > bS_i$, the C_i^2 which appears in the pricing formula incites to diminish water consumption.

A deterministic approach, without acquisition of information between the reservation date and the consumption date, is sufficient in order to study some of the properties of this pricing. Of course other properties directly linked to stochastic variables (as the climate) cannot be studied here and are the object of further researches.

But we must note that since C_i depends on S_i , we must take this relationship into account in optimizing the volumes reserved and consumed by the farmer i .

3.2 The maximization problem of farmer i

When choosing the values of his control variables S_i and C_i , the farmer must decide of the optimal value of C_i knowing the optimal value of S_i previously announced. Therefore each farmer must solve

$$\max_{S_i} \left[\max_{C_i} (h_i(C_i) - F(S_i, C_i)) \right] \quad (2)$$

where the production function of farmer i , h_i , is an increasing and concave function.

3.2.1 The maximization problem in C_i

We note $G(S_i, C_i) = h_i(C_i) - F(S_i, C_i)$, and we calculate the solution of the maximization of $G(S_i, C_i)$ as a function of C_i . We have

$$\frac{\partial G_i(S_i, C_i)}{\partial C_i} = \begin{cases} h'_i(C_i) - 2(1-a)D \frac{C_i}{S_i} & \text{if } bS_i < C_i \\ h'_i(C_i) - (1-a)bD & \text{if } bS_i > C_i \end{cases} \quad (3)$$

- For $bS_i < C_i$, we note $C_i^-(S_i)$ the solution in C_i of

$$h'_i(C_i) = 2(1-a)D \frac{C_i}{S_i} \quad (4)$$

With a simple derivation of this last equation, it is easy to see that

$$C_i^{-'}(S_i) = \frac{2(1-a)DC_i}{2(1-a)DS_i - h''(C_i)S_i^2} > 0 \quad (5)$$

Therefore $C_i^{-'}(S_i)$ is an increasing function of S_i .

We remark by the way that when $bS_i < C_i$, we have

$$2(1-a)D \frac{C_i}{S_i} > 2(1-a)bD > (1-a)bD \quad (6)$$

- For $bS_i > C_i$, we call C_i^+ the solution in C_i of

$$h'_i(C_i) = (1-a)bD \quad (7)$$

We note that this solution does not depend on S_i .

The preceding remark, the concavity of h_i , and the definition in (4) and (7) of C_i^- and of C_i^+ imply that

$$C_i^-(S_i) < C_i^+ \quad (8)$$

We can easily deduce that the optimal solution C_i^{sol} of (2) for S_i given depends on the relative positions of $C_i^-(S_i) < C_i^+$ and of bS_i :

$$C_i^{sol} = \begin{cases} C_i^-(S_i) & \text{if } S_i < C_i^-(S_i)/b \\ bS_i & \text{if } C_i^-(S_i)/b \leq S_i \leq C_i^+/b \\ C_i^+ & \text{if } S_i > C_i^+/b \end{cases} \quad (9)$$

Note that this formula gives a relation $C_i^{sol}(S_i)$ that depends on the parameters of the regulator and of the profit function h_i of farmer i . When starting from small S_i ,

$C_i^{sol}(S_i)$ is first an increasing function of S_i , then it is a linear function in S_i , and finally it is a constant.

3.2.2 The maximization problem in S_i

When solving the maximization of our problem in S_i , knowing the optimal value C_i , which is generally, as we saw, a function of S_i , we must consider the relation between these two variables.

- If $S_i < C_i^-(S_i)/b$, we must solve

$$\max_{S_i} \left(h_i \left(C_i^-(S_i) \right) - F \left(S_i, C_i^-(S_i) \right) \right) \quad (10)$$

and the first-order condition gives

$$h_i'(C_i^-(S_i))C_i^-(S_i) = D \left[a + (1-a) \frac{2C_i^-(S_i)C_i^-(S_i)S_i - (C_i^-(S_i))^2}{S_i^2} \right] \quad (11)$$

- If $C_i^-(S_i)/b \leq S_i \leq C_i^+/b$ we must solve

$$\max_{S_i} \left(h_i(bS_i) - D(aS_i + (1-a)b^2S_i) \right) \quad (12)$$

for which the first-order condition is

$$bh_i'(bS_i) = D[a + (1-a)b^2] \quad (13)$$

- and if $S_i > C_i^+/b$ the maximization problem is:

$$\max_{S_i} \left(h_i(C_i^+) - F(S_i, C_i^+) \right) \quad (14)$$

that does not have a solution, which means that the farmer will at least consume bS_i (as consuming less would decrease his production without decreasing his water bill; in other words we have $bS_i \leq C_i$).

To obtain the optimal solution of our problem in S_i , we must analyze the admissibility of solutions of (11) and (13).

Theorem

The optimal strategy of farmer i is

$1/S_i = C_i \sqrt{(1-a)/a}$ if $0 < \frac{b^2}{1+b^2} < a < 1$, where C_i is the solution of

$$h_i'(C_i) = 2D\sqrt{a(1-a)} \quad (15)$$

$2/S_i = C_i/b$ if $0 < a < \frac{b^2}{1+b^2} < 1$, where C_i is the solution of

$$h_i'(C_i) = \frac{D(a + (1-a)b^2)}{b} \quad (16)$$

Proof of the theorem

We start by introducing a Lemma.

Lemma

$$\max_{S_i} \left[\max_{C_i} (h_i(C_i) - F(S_i, C_i)) \right] = \max_{S_i, C_i} [h_i(C_i) - F(S_i, C_i)] \quad (17)$$

Proof of the Lemma

In Section 3.2.1 of this chapter, we have shown that the solution of

$$\max_{S_i} \left[\max_{C_i} (h_i(C_i) - F(S_i, C_i)) \right] \quad (18)$$

is given either if $bS_i = C_i$ (border solution) by the maximization in S_i of $G(S_i, C_i)$ or if $bS_i < C_i$ (interior solution) by $h'_i(C_i) = 2(1-a)D \frac{C_i}{S_i}$ (Eq. (4)).

Now if we solve the problem

$$\max_{S_i, C_i} [h_i(C_i) - F(S_i, C_i)] \quad (19)$$

its interior solution (with $bS_i < C_i$), knowing that (the first equivalence being due to the fact that $G(S_i, C_i)$ depends on S_i only through $F(S_i, C_i)$ and not through h_i)

$$\frac{\partial G(S_i, C_i)}{\partial S_i} = 0 \Leftrightarrow \frac{\partial F(S_i, C_i)}{\partial S_i} = 0 \Leftrightarrow S_i = \sqrt{\frac{1-a}{a}} C_i \text{ and } b\sqrt{\frac{1-a}{a}} < 1 \quad (20)$$

is given by

$$\frac{\partial G(S_i, C_i)}{\partial S_i} = 0 \Leftrightarrow h'(C_i) = 2(1-a)D \frac{C_i}{S_i} \quad (21)$$

which coincides with (4). Replacing this equation in (11), we obtain

$$2(1-a)D \frac{C_i}{S_i} C'_i = D \left(a + \frac{(1-a)2C_i C'_i}{S_i} - (1-a) \frac{C_i^2}{S_i^2} \right) \quad (22)$$

Simplifying we find Eq. (18) so that the interior solution coincides with the solution of (2). The border solutions are also the same (i.e., $bS_i = C_i$) for (2) and for (19). Finally, both solutions are the same.

We now return to the demonstration of the Theorem itself. Thanks to the Lemma, we can now compute the solution of (2), by computing the solution of

$$\max_{S_i, C_i} [h_i(C_i) - F(S_i, C_i)] \quad (23)$$

- If $bS_i < C_i$,

then (23) can be written as

$$\max_{S_i, C_i} \left(h_i(C_i) - D \left(aS_i + (1-a) \frac{C_i^2}{S_i} \right) \right) \quad (24)$$

And the first order conditions give

$$a / \frac{\partial [h_i(C_i) - D(aS_i + (1-a)\frac{C_i^2}{S_i})]}{\partial S_i} = a - \frac{(1-a)C_i^2}{S_i^2} = 0 \quad (25)$$

which is equivalent to

$$S_i = \sqrt{\frac{1-a}{a}} C_i \quad (26)$$

We remark that this implies, as $bS_i < C_i$, that

$$b\sqrt{\frac{1-a}{a}} < 1 \quad (27)$$

and

$$b / \frac{\partial [h_i(C_i) - D(aS_i + (1-a)\frac{C_i^2}{S_i})]}{\partial C_i} = h'(C_i) - D\frac{(1-a)2C_i}{S_i} = 0 \quad (28)$$

which is equivalent to

$$h'(C_i) = 2D\sqrt{a(1-a)} \quad (29)$$

- If $bS_i \geq C_i$,

then (23) can be written as

$$\max_{S_i, C_i} (h_i(C_i) - D(aS_i + (1-a)bC_i)) + \mu(bS_i - C_i) \quad (30)$$

with μ the dual variable associated to the constraint $bS_i \geq C_i$.

The first-order conditions give here:

$$a / \frac{\partial [h_i(C_i) - D(aS_i + (1-a)bC_i) + \mu(bS_i - C_i)]}{\partial S_i} = -Da + \mu b = 0 \quad (31)$$

and

$$b / \frac{\partial [h_i(C_i) - D(aS_i + (1-a)bC_i) + \mu(bS_i - C_i)]}{\partial C_i} = h'(C_i) - D(1-a)b - \mu = 0 \quad (32)$$

The solution of these equations is.

$$C_i = bS_i, \mu = \frac{Da}{b} > 0 \text{ and } h'(C_i) = D\left[(1-a)b + \frac{a}{b}\right] = D\left[\frac{(1-a)b^2 + a}{b}\right] \quad (33)$$

Remark 1

The optimal solution is a continuous function of parameters a and b . Moreover, the regulator can choose parameters a and b in order to enforce an interior solution or a border solution.

Remark 2

Note that in 2/ of the theorem

$$\lim_{b \rightarrow 0} \left(\frac{D(a + (1-a)b^2)}{b} \right) = \infty \quad (34)$$

If we choose b small enough and therefore a small enough to remain in case 2/, (20) incites the farmers to use less water, that is, $C_i \rightarrow 0$ when $b \rightarrow 0$. But in general we cannot draw any conclusion on the value of S_i .

In conclusion the WUA manager may use these two parameters a and b in order to decrease the water consumption, but he cannot make water decrease at discretion since as in our example he might decrease also the reserved volume and at the end the budget equilibrium would not be satisfied.

Note also that in 1/ of the Theorem, we cannot make the consumption C_i decrease at will, since the maximum value of $h'_i(C_i)$ is equal to D according to Eq. (15).

Figure 1 shows how S_i must be tightly correlated to C_i by the farmer in order to obtain a good remuneration $G_i(S_i, C_i) = h_i(C_i) - F(S_i, C_i)$ for his activities. (Numerically, it is computed with the following functions and values: $h_i(C_i) = 2.C_i^{0.5}$; $a = 1/3$; $b = 0.7$; $D = 2$; negative values have been replaced by 0). A slight deviation from the optimum value of S_i at the reservation time, and of the optimal consumption C_i , once S_i is chosen, will diminish considerably the value of the gain G . This means that from the value of S_i , the WUA manager is able to predict accurately the level of the water demand.

3.3 The budget equilibrium constraint

In this section, we study the conditions in which the budget equilibrium may be obtained, or in other terms, in which

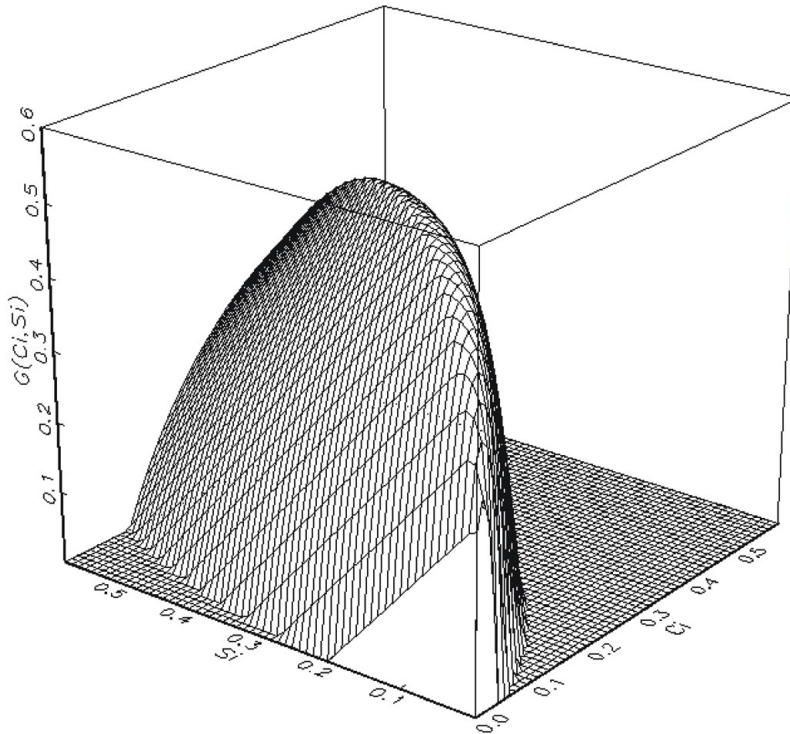


Figure 1.

Representation of $G(C_i, S_i)$ as a function of C_i and of S_i . Numerical values: see text.

$$\sum_i F(S_i, C_i) = B \quad (35)$$

The WUA manager may choose parameters a and b in such a way that

1/ either $0 < \frac{b^2}{1+b^2} < a < 1$ and then $S_i = C_i \sqrt{(1-a)/a}$ according to the Theorem; we know then that

$$C_i = [h'_i]^{-1} \left(2D \sqrt{a(1-a)} \right) =: g_i \left(2D \sqrt{a(1-a)} \right) \quad (36)$$

and the budget equilibrium constraint (35) must be written as

$$2\lambda B \sqrt{(1-a)/a} \sum_i C_i = 2\lambda B \sqrt{(1-a)/a} \sum_i g_i \left(2\lambda B \sqrt{a(1-a)} \right) = B \quad (37)$$

which gives

$$2\lambda \sqrt{(1-a)/a} \sum_i g_i \left(2\lambda B \sqrt{a(1-a)} \right) = 1 \quad (38)$$

If we assume in order to facilitate the presentation of the demonstration that $h_i(C_i) = \frac{C_i^{\alpha_i}}{\alpha_i}$, with $0 < \alpha_i < 1$, which reminds us of a Cobb–Douglas production function, this last equation becomes

$$f(\lambda) =: 2\sqrt{(1-a)/a} \sum_i \lambda^{\frac{\alpha_i}{\alpha_i-1}} M_i = 1 \quad (39)$$

$$\text{where } M_i =: \left(2B \sqrt{a(1-a)} \right)^{\frac{\alpha_i}{\alpha_i-1}} \quad (40)$$

Noting that since $\frac{\alpha_i}{\alpha_i-1} < 0$, we have $\lim_{\lambda \rightarrow 0} f(\lambda) = +\infty$ and also $\lim_{\lambda \rightarrow \infty} f(\lambda) = 0$. As $f'(\lambda) < 0$, we deduce that there exists a unique λ which verifies (39).

2/ or $0 < a < \frac{b^2}{1+b^2} < 1$ and then $bS_i = C_i$, according to the Theorem.

Previously we showed that

$$C_i = [h'_i]^{-1} \left(\frac{D(a + (1-a)b^2)}{b} \right) =: k_i \left(\frac{D(a + (1-a)b^2)}{b} \right) \quad (41)$$

Assuming here too that $h_i(C_i) = \frac{C_i^{\alpha_i}}{\alpha_i}$, the budget equilibrium constraint (39) can be written as

$$g(\lambda) =: A \sum_i \lambda^{\frac{\alpha_i}{\alpha_i-1}} N_i = 1 \quad (42)$$

with $A =: \frac{D(a+(1-a)b^2)}{b}$ and $N_i =: (BA)^{\frac{1}{\alpha_i-1}}$, and we obtain the same conclusion as in 1/.

So, once parameters a and b are chosen for considerations of water savings, the WUA manager can force the system to be in budgetary equilibrium with the choice of the parameter λ value. Of course, not knowing the true value of α_i parameters, or more generally ignoring the precise form of the $h_i(C_i)$ functions, he will not be able to compute directly the optimal value of λ , but the existence result on a unique λ value and the monotonicity of $f(\lambda)$ and of $g(\lambda)$ allows him to find the correct value by trials and errors.

4. Conclusion

We have shown here how it is possible with a pricing system based on two variables, reservation and consumption, for the WUA manager to get enough information in order to anticipate any disequilibrium between water demand and supply, when it is always possible to change the choice of the cultures. Moreover changing the parameters allows the WUA manager to modify the volume consumed by the farmers, which is especially useful when searching a decrease of the water consumption. Translated in a two-entry table, this method is simple enough to be understood by each farmer and quite acceptable since associating the pursuit of fairness, efficiency, and adaptability.

At last, with a judicious choice of the value for the parameters, it is possible to incite the farmers to be more or less acute in the choice of their reservation and consumption values. This pricing system should therefore allow a more efficient use of the water resource by the farmers, by the way decreasing the constraints on other economic sectors and on the environment.

The need for a better management of irrigation water is now recognized, and the potentialities of original pricing systems (see, for example, [22]) are confirmed by many work in economics, carried out in different contexts such as those presented by [23] in semi-arid climates, or [24], and [25] in different European countries.

Further researches are nevertheless needed to study how such a system keeps or increases its advantages when we take into account the fact that in many countries the water supply may be stochastic (see, for example, [26]). It would also be important to study the strategic interactions between farmers, as well as the different inter-annual dynamics that can be put in place, in order to facilitate the development of agricultural activities, while still under budgetary constraint (see [27]). In addition, the acquisition of information between the reservation (during the wet vegetation season) and the peak consumption (during the dry vegetation season) can be sequential. Taking this into account can lead to an even better valorization of the water resources, through the implementation of an adapted pricing policy. This leads to other refinements which are the aim of other present researches.

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Conflict of interest

The authors declare that there is no conflict of interest.

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