Assessment of groundwater management instruments in a conjunctive use system:
A linear programming approach

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Abstract

The objective of this paper is to compare several economic instruments which may be implemented to mitigate current farmers' groundwater withdrawals in a multi-resource system. We conduct a fined-tuned field work with farmers to understand the key points of substitution between underground and surface water at the farm level. A linear programming framework has been used to model fruits and vegetable production systems. It shows that groundwater demand is sensitive to its variable cost, advocating for effectiveness of price-based instruments to mitigate underground irrigation withdrawals. Although economists often advocate for such instruments superiority, volumetric surface water pricing and fees on groundwater consumption partially fail to satisfy our criteria for instruments assessment. We finally support the implementation of a binomial surface water pricing or a quota system on groundwater. The latter could be framed by the so-called "*Organism Unique*" introduced by the 2006 Water and Aquatic Environment Law.

Keywords: Groundwater Management, Economic Instruments, Conjunctive Use, Linear Programming.

1. Introduction

The rapid increase of population pressure in coastal areas exacerbates conflicts over the use of a limited resource, freshwater. This is particularly true in Mediterranean regions where population migrations and tourism induce an increasing pressure on water resources. Conflicts may appear then between the former traditional users, irrigating farmers, and new incomers, the tourism sector and the ever-growing urban population.

This is particularly the case for groundwater, which is a very attractive resource:

- It is easy to extract water, because groundwater if often available at a low depth (FORNÉS ET AL., 2005).
- Groundwater is often cheaper than surface water: aquifers play a double role of reservoir and distribution network. Technological improvements (a borehole rather than a well, a pump rather than a water wheel …) have further highly decreased extracting costs (LLAMAS and MARTINEZ-SANTOS, 2005). Surface water costs tend conversely to increase for farmers: public financing programs for irrigation are reducing and there is a will to apply a cost recovery principle recommended in Europe by the Water Directive Framework (WFD) (Directive 2000/60/EC).
- Groundwater quality is usually good indeed even potable and is naturally filtered. It can be directly utilised for a drinkable use or a precision irrigation.
- Groundwater is also available 24h/24 contrary to many irrigation networks, where there are rotations' constraints.
- Finally, groundwater is less subject to temporary withdrawals' restrictions during droughts, contrary to surface water. Groundwater may then be defined as a dynamic stock of water (KOUNDOURI, 2004) balancing water demand during dry periods. Diminishing the temporal scarcity of water, groundwater is highly valuable for both tap water suppliers and irrigating farmers in arid or semi-arid contexts.

Consequently, surface networks are frequently forsaken by farmers for individual wells when both water resources are available. In such conjunctive use systems, groundwater overexploitation may appear although underused surface water supply does exist. A conjunctive management is therefore needed.

Such a multi-resource context has already been included in models seeking to simulate links between surface and groundwater uses under conjunctive management of water resources. They focus on optimal spatial (CHAKRAVORTY and UMETSU, 2003), temporal (KNAPP and OLSON, 1995; TSUR and DINAR, 1997) or both (NOEL et al., 1980) allocation of water. Although they are well documented, few studies on conjunctive use systems focus on the implementation of economic instruments. SCHUCK and GREEN study a supply based water pricing structure of a conjunctive management system, defined as an area wherein "*surface supplies are managed jointly with groundwater resources*" (SCHUCK and GREEN, 2002).

Since most multi-resources systems are not managed jointly, we make a distinction between conjunctive management systems (rarely seen in practice) and conjunctive use systems, where both types of resources are managed separately or unmanaged at all. In the later case, surface and groundwater uses are competing and the management of one resource may endanger the sustainability of the other. Too few papers address groundwater management by taking into account the substitution process existing between surface and underground resources.

Our purpose is to address how a multi-resource system could be shifted from a conjunctive use system to a conjunctive management one. To do so, we assume that economic tools can allow this shift; we also assume that excluding agricultural groundwater uses may not be economically righteous since optimal groundwater extraction plans could include irrigation from wells.

We compare four management tools and their impact on farmers' behaviour. We develop then a microeconomic framework to model the irrigation decision process in a multi-resource context through linear programming methods. Our method is applied to the French case study of the Roussillon floodplain where two resources exist: groundwater and surface water. Surface water is distributed through a collective irrigation networks while groundwater is withdrawn through individual boreholes.

In the present paper, section 2 describes the management tools that will be later compared. Section 3 focuses on the description of our modelling approach which is applied to our case study in section 4. We then present and discuss the outcomes of our model in section 5 before concluding in section 6.

2. Management tools

The instruments we aim at comparing will be assessed thanks to five criteria we will first describe, before presenting more specifically a set of selected instruments which can be implemented to manage groundwater in a conjunctive use system.

2.1. The five criteria to compare management tools

Aggregate Income

The neoclassical framework intends at comparing natural resources management instruments through the efficiency criterion. Price-based instruments are often seen as more efficient than quantitative tools as they tend to reach marginal costs of use abatement, mainly when marginal abatement costs are heterogeneous across agents (STERNER, 2003). Our methodological framework impedes us to compare instruments' efficiency. We will use in this paper the aggregated income of farmers and resource managers (the surface water supplier and the water agency) for each groundwater consumption level as a proxy of efficiency.

Aggregated income should not however be addressed as the sole criteria for water management instruments assessment. Price-based instruments are actually not always chosen by policy makers and quantitative mechanisms still remain the most encountered instrument type worldwide (BARDE, 1991): theoretical gains from price-based instruments may be quite small – or even negative – in practice (OATES, 1990) and their implementation constrained by the informational context. Therefore, in this paper, we pay further attention to four other objectives: acceptability, predictability, durability and implementability.

Acceptability

Acceptability is a key issue for the enforcement of instruments since conditions of the implementation are often bargained with stakeholders in practice. When policy makers are submitted to citizens' vote, political aspects arise making acceptability of central concern. We approximate in this paper the instruments' acceptability by the level of farmers' income.

Predictability

We define predictability as the ability of an instrument to reach as close as possible a targeted level of abatement. Predictability helps water managers to secure receipts and then their budget balance. It provides further to policy makers credibility and secures "returns" on costs supported by authorities (implementation costs) and users (taxes, fees or opportunity costs). We evaluate the level of predictability of an instrument through the sensitivity of groundwater consumption to the instrument implementation (fee level, volumetric price…).

Durability

Durability of infrastructures ensures the durability of resource exploitation. We focus on the sustainability of surface water supply. In collective irrigation systems, operation and maintenance costs of surface water should be recovered by the surface water supplier earnings in order not to fall into the vicious circle of maintenance negligence and irrigation water demand decrease (PERRY, 2001). To assess this cost recovery, we look further at surface water supplier receipts.

Implementability

Finally, an instrument has to be implementable: it is therefore important to check if the legal framework allows such instrument and if information needed for instruments' enforcement is available at an acceptable cost. We call this criterion implementability.

Efficiency, acceptability, predictability, durability and implementability are the five criteria which will allow us to compare the following economic instruments.

2.2. Description of two kind of tools to manage groundwater in a conjunctive use system

Two types of management instruments of groundwater can be identified in multi-resource context: direct instruments impacting farmer's behavior toward groundwater and indirect instruments impacting farmer's behavior toward surface water and thus using the substitution between resources to manage groundwater withdrawals.

Direct instruments

Direct instruments are based on price signals (taxes, fees or tariff) or on quantities (quotas).

Tax and fees

Tax or fee can be implemented to allow considering all costs and benefits (and mainly the social ones) which are not taken into account by current prices: put at an optimal level, it internalizes then the externalities, following the Pigovian framework[1]. The difference between the two instruments deals with the final destination of fiscal receipts: fees on water use are collected to fund specific water recuperation actions (struggle against water pollution, supply increase or subsidies for technological changes), and taxes go to the general state budget, without any specific destination.

As external costs induced by groundwater extraction are spontaneously not taken into account by users, several countries implemented fees on irrigation water withdrawals. Those fees are however noticeably underestimated compared to the optimal tax level needed to incite farmers' consumption to reach the social optimum. The pursued objective is indeed in many countries more to fund water authorities' financial needs (preservation actions and afferent administrative costs) (DA MOTTA et al., 2004) than to reach the optimal desired level of consumption: it leads therefore to overconsumption.

Pricing instrument usually provokes reluctance among users: for the same consumption level, it decreases users' income; people are also poorly confident in its effectiveness and claim that the outcome of its implementation remains *ex ante* uncertain. Therefore, we thus foresee its acceptability to be low and its predictability to be uncertain.

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[1] See Provencher and Burt (1993) for a comprehensive survey on externalities ensuing from groundwater extraction (PROVENCHER and BURT, 1993).

In the present paper, we will test different levels of fees on groundwater use implemented by the French Water District Agency, as it actually exists, but at a too much low level to incite to lower irrigation water withdrawals.

Quotas

Quotas belong to quantity-based instruments. The quota imposes an upper limit to water consumption and can be specified using volumetric, discharge or time units (eventually combined) (MONTGINOUL, 1998). In general, it is accompanied of technology standards (on the deep and the location of boreholes, on the type of pumping material, etc.).

Quota directly constraints users instead of indirectly modify their behaviour through market signals (BOHM and RUSSEL, 1985). It then represents for water manager a guaranty to reach automatically the desired abatement level and remains the most suited instrument for environmental issues inducing irreversible (BARDE, 1991) or heavily dangerous effects (i.e. with steep marginal benefit function) (BAUMOL et al., 1988).

A quota system on groundwater consumption will thus be the most predictable instrument we attempt to compare. Most interviewed farmers on the field point out that they will be more likely to accept a quota system than fees on groundwater. We expect our model to reach the same conclusion.

In the present paper, we will test the implementation of volumetric quotas. Theses quotas could be allocated to irrigation farmers by water managers (called "*Organismes Uniques*") which have to be created (before the end of 2010) on every water resource considered as structurally scarce (article 21st of the 2006 French Water Law): these water managers will be in charge of sharing the allocated volume between farmers who withdraw water from the same water resource (in this paper, the aquifer).

Indirect instruments

Surface water pricing

As surface water is an (imperfect) substitute to groundwater, surface water pricing – implemented to cover costs of surface irrigation network – participates to the level of groundwater consumption. Its level and its structure are therefore important to understand the choice of water resource made by farmers.

Water pricing structure is often built to reflect costs structure:

- Open canal irrigation systems face important fixed costs while the conveyance cost of an additional cubic meter is almost null, most of them only apply a flat price structure.
- Pressurized on-demand systems traditionally apply a binomial tariff accounting for subscribed flow (or acreage owned) and water consumption[2] because they encounter both fixed and variable costs. Although it remains a side effect of the pricing structure, the volumetric part acts as an incentive toward a more effective surface water use. Some argue in favour of a purely volumetric irrigation water pricing.

The choice of surface water pricing structure depends also on technical constraints like water pipe size or pumping capacity. In the case study we describe in section 4, the surface water manager is more constrained by water flows in the delivery infrastructure than by water quantity: this explains that he chooses a binomial pricing structure where the fixed part depends on subscribed flow and where each cubic meter per hour subscribed gives right to a free water allotment.

[2] See GLEYSES for a precise snapshot of irrigation network pricing in France (GLEYSES, 1998).

To summary, surface water pricing structure is delimited by a set of technical, structural and budgetary constraints which must be satisfied to guaranty the durability of delivery networks. But surface water manager designs often its water pricing structure without taking into account the possible substitute of its surface resource and then can face unexpected decreasing water demand. To go further, we can imagine surface water pricing structures or levels that allow helping farmers to shift in consumption from the aquifer to surface water.

In the present paper, we will test different levels of surface water pricing and two pricing structures that the surface water manager could put to price its services. We will then compare: the current binomial pricing structure (with a fixed part proportional to the subscribe flow) to a purely volumetric surface water pricing with a limited subscribed flow.

3. Model description

3.1. Methodology used

We use a linear programming framework. LP has been used for decades in agricultural production economics (BOUSSARD and DAUDIN, 1988). It relies on the neoclassic rationality hypothesis, standing that farmers maximize their individual profits through the optimal combination of inputs, crops and acreages under economic, agronomic and technical constraints. The originality of our model relies mainly on the fine-tuned field work done with farmers on the substitutability of both surface and groundwater. This allows us to infer the impact of economic instruments on production systems[3].

3.2. Optimization process

Our model relies on the static optimization of farmer's annual profit (Π), expressed as the sum over crop c of annual p.ha. net benefit (NB_c) minus p.a. total water expenditures according to resource r (WC_r) and minus labour cost (LC). We assume farmers to be risk neutral. We partition the year into 24 equal periods (p) as labour and water needs are typically seasonal.

(1) $\text{Max } \Pi_{(Xc,WQr,FLOWr,PL,SLp)} = \Sigma_c NB_c.X_c - \Sigma_r WC_r - LC$

3.3. Water equations

We split water costs into fixed and variable costs (FC_r and VCr) (2). Fixed costs are proportional to the delivery flow of water ($FLOW_r$) (3) and variable costs gather variable water costs (energy cost or variable part of water pricing) and volumetric fees.

(2) $WC_r = FC_r + (VC_r + FEE_r).WQ_r$

(3) $FC_r = FIX_r.FLOW_r$

Optimization is further constrained by:

- <u>A periodic water need constraint</u> (4): periodic water needs ($WN_{c,p}$) is saturated by rain ($RAIN_p$) and irrigation water quantity ($WQ_{r,p}$) from different resources.

(4) $\Sigma_c WN_{c,p}.X_c \leq RAIN_p + \Sigma_r WQ_{r,p}$

- <u>A water delivery constraint</u> (5): periodic water needs delivery should be covered by the sum over resources of delivery flows ($FLOW_r$) multiplied by the irrigation, duration (ID_r). This guarantees the needs to be covered even if rainless periods occur.

(5) $\Sigma_c WN_{c,p}.Xc \leq \Sigma_r ID_r.FLOW_r$

[3] Several authors recommend the Positive Mathematical Programming (PMP) developed by Howitt in order to reproduce more accurately farmers' decisions (HOWITT, 1995). However, the lack of precise agricultural data on the field impedes a precise calibration of the model.

3.4. Labour equations

Our model is accounting for seasonal and permanent labour costs (6) which equal the sum over periods of the labour quantity (SL_p, *PL.PLA*) multiplied by wages (*SLW*, *PLW*) (7)(8).

(6) $LC = SLC + PLC$

(7) $PLC = PLW.PL.PLA$

(8) $SLC = SLW.\Sigma_p SL_p$

Permanent tasks are done by permanent workers and family according to their availability (*PLA*, *FLA*) (9). We assume further that permanent workers (*PL*) can operate as seasonal workers in some periods, once the permanent labour needs ($PLN_{c,p}$) of crops are fulfilled. This is introduced by the residual permanent labour (RPL_p) (9)(10). The sum of seasonal and residual permanent labour must satisfy seasonal labour needs ($SLN_{c,p}$) (10).

(9) $\Sigma_c PLN_{c,p}.X_c + RPL_p \leq FLA + PL.PLA$

(10) $\Sigma_c SLN_{c,p}.X_c \leq SL_p + RPL_p$

3.5. Land constraints

Land constraints are finally computed, incorporating land limitation through intra-annual crop sequencing constraints with winter crops (*wc*) and summer crops (*sc*) (11)(12).

(11) $\Sigma_{wc} X_{wc} \leq SAU$

(12) $\Sigma_{sc} X_{sc} \leq SAU$

The endogenous variables of our model are crops acreages (X_c), water consumption from each resource (WQ_r), water flow subscribed to surface water manager or the pumping capacity from wells ($FLOW_r$) and permanent and seasonal workers hired on farm (PL and SL_p).

3.6. Instrument implementation

The different types of instruments presented in section 2.2 are tested: quotas or fees on groundwater and a change in surface water pricing structure and level (the decrease of both parts of the binomial structure or the implementation of a volumetric pricing structure).

Technically, they are integrated in our model as follow: quotas on groundwater are incorporated by adding a volumetric constraint over water quantities withdrawn from wells. Taxes or fees on underground consumption are introduced into the water cost equation (2) as discount on surface water and changes in the pricing structure.

4. Case study

4.1. Water issue

The Roussillon floodplain is located in the extreme south of the French Mediterranean coastline and lies over a pristine multi-layer aquifer. The production of drinkable water (about 45 $bn.m^3$) relies exclusively on groundwater and constitutes the priority consumptive use. Agricultural uses however routinely exist (about 25 $bn.m^3$) with about 1 300 farmers withdrawing from individual wells. Public authorities and water managers are aiming at limiting farmers' groundwater consumption to preserve the underground resource. As the irrigated agriculture constitutes an important sector of the local economy, this limitation occurs firstly where substitution with surface water is possible (CG66, 2003).

We focus more precisely on the pressurized on-demand collective network of Villeneuve-de-la-Raho whose water supply is secured by a 14 bn.m^3 dam. The network spreads over more than 33 km² and could be extended to 52 km², while only about 11 km² are today cultivated through network waters. A free-access shallow aquifer (but incurring a variable cost estimated between 0.02 and 0.04 €/m^3) is underlying the whole area, directly competing surface water consumption. As many other irrigation collective networks, the Villeneuve-de-la-Raho area constitutes then a conjunctive use system.

The current water pricing is a binomial one with a fixed part proportional to subscribed flows giving right to an initial water allotment. The variable part of the tariff account only for the cubic meters beyond this allotment. This variable part is lower than the mean price of the water initially allotted. Two tariffs are basically proposed by the supplier: the "*Base*" ("*Annexe*") tariff favouring those consuming high (low) volume relatively to the subscribed flow. Table 1~~Table 1~~ details those tariffs.

Table 1: Tariff applied by the surface water supplier

Tariff	Allotment	Fixed Part	Volumetric Part
"*Base*"	600 m^3/m^3/h	74.006 €/m^3/h	0.0629 €/m^3
"*Annexe*"	300 m^3/m^3/h	55.456 €/m^3/h	0.1258 €/m^3

Farmers are incited to minimize its subscribed flow (and then its water allotment) by splitting their farm in different irrigation units and implementing a rotation between those units within farms[4]. Consequently, the pricing structure ensures the network manager to provide water even during pick period as unlimited subscribed flows may congest the network. The structure is thus not shaped to incite farmers to save water nor to account for substitution between resources.

4.2. Farm types

We focus on the fruits (27%) and vegetables (62%) sectors which represent about 90% of irrigated acreages of our case study (RGA, 2000). A survey done with local specialists of the agricultural sector and irrigating farmers has concluded that there are two main irrigating types of farm on the area: the first type is specialized in orchards such as peach trees and apricot trees while the second type grows vegetables like salad, potato or artichoke. We limited the choice of crops because market access is particularly constraining in the area, limiting farm diversification. The outcome of our model seems to local specialists relatively close to field reality. They are displayed in Table 2~~Table 2~~.

Table 2~~2~~: Main features of farm types

Farm Type	Type 1: Fruit producer	Type 2: Vegetable producer
Area	20 ha	10 ha
Familial labour	1 person	1 person
Crop distribution	Early Peach: 52% Peach: 36% Apricot: 12%	Artichoke: 7% Salad: 45% Potato: 85%

[4] He decreases the flow needed for irrigation while increasing irrigation duration.

4.3. Climatic features

The Roussillon floodplain is one of driest French area. Rainfall average level is about 570 mm p.a. with a high intra and inter-annual variability. The whole crops cultivated there must be irrigated but vineyard. We run our model over different seasons in term of rainfall to address the inter-annual variability impact on farmer's behaviour. Wet, mean and dry years are computed with a 30% deviation from average rainfall calculated with data over the 1971-2008 period. Intra-annual variability is addressed via the multi-periodic structure of the model.

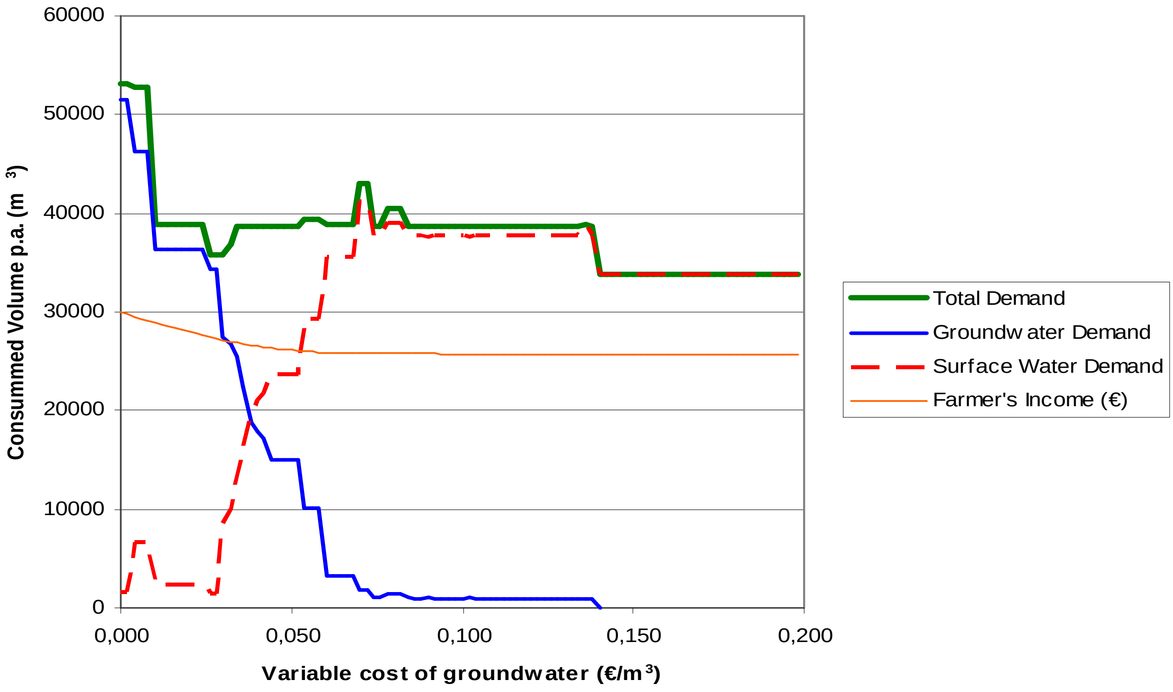
5. Results

Results presented in this section firstly deal with the present shape of groundwater and surface water demands derived from our model, and then compare the different management instruments according to the five criteria presented in section 2.1.. To simplify the presentation, results concern here only the type 2 (i.e. vegetable producer). Furthermore, we observe that the sensitivity of the model to rainfalls remains small as dry, mean and wet years data lead to relatively similar outcomes: it explains that we have not introduced farmers' risk attitudes towards rainfalls.

5.1. Groundwater demand responsiveness to price signal

Figure 1~~Figure 1~~ draws the derived demand for groundwater of the type 2 farm from our linear programming models. Total water demand (bold curve) is inelastic, but groundwater demand (decreasing curve) is highly elastic to groundwater variable extraction cost (energy cost, water fee…) due to the substitution between ground and surface resources. It is particularly the case for the current variable cost of groundwater, corresponding to one of the most sensitive part of the groundwater demand curve.

Figure 1: Derived water demand of a French vegetable producer and impact on its income.



Derived groundwater demand elasticity and substitutability between resources advocate for the effectiveness of groundwater management policy relying on price instruments targeting surface and groundwater.

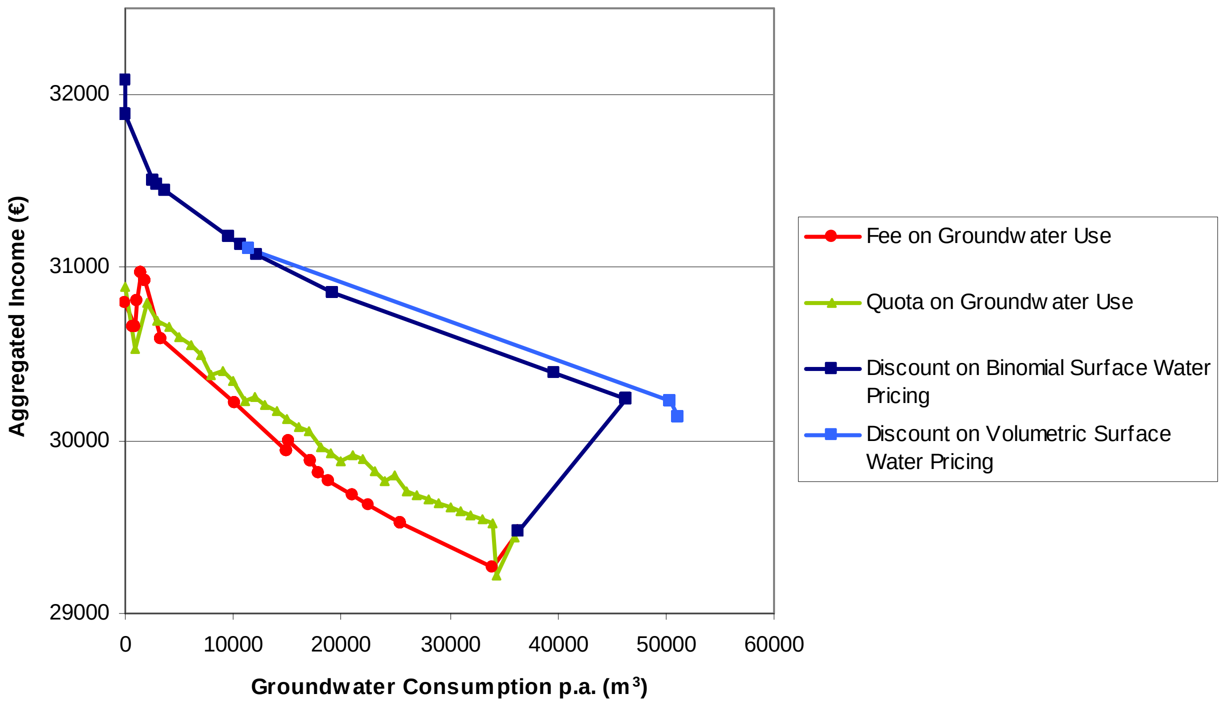
5.2. Instruments comparison

Price instruments (fees on groundwater consumption, discount on surface water pricing, and surface network tariff structure change) and volumetric quotas on groundwater are now compared on the basis of the five criteria described in section 2.1. Our purpose does not consist in identifying the desirable groundwater withdrawals level, but rather to know for each level defined by a hypothetical groundwater manager (the "*Organisme Unique*") the most suited instrument.

Aggregate income of farmer and resource managers

Figure 2~~Figure 2~~ plots the aggregate income generated by both surface and groundwater consumption, i.e. the sum of farmer's, the surface water supplier's and the Water Agency's earnings, according to the groundwater consumption level. Both volumetric and binomial surface water pricing discounts enhance the aggregate income. The difference with quotas and fees on groundwater remains however small (about 3%) and the instruments slightly converge at high groundwater consumption abatement levels (the difference shrinks until about 1.5%). The total income criterion is then not sufficient to discriminate the selected instruments.

Figure 2~~2~~: Aggregate income generated by the French vegetable producer groundwater consumption.



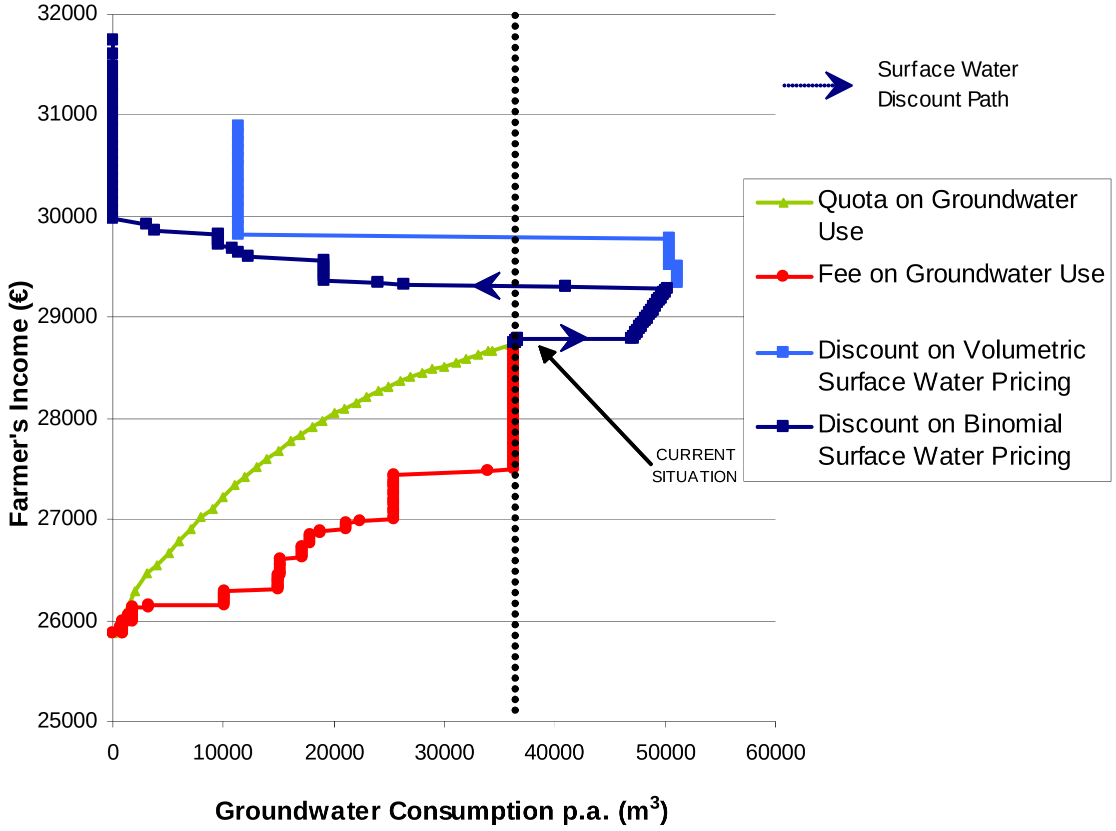
Acceptability

Fee and quota on groundwater decrease farmers earning when imposing reduction of underground withdrawals (see Figure 3~~Figure 3~~ where dots represent simulation outcomes for different levels of discount, quotas or fees): a fee reduces sharply farm income in the early abatement level while quotas act in a more steady way; the two instruments finally converge at high abatement levels. Furthermore, farmers may prefer a discount on surface water as it slightly increases their income with abatement: for this reason, we assume that this type of instrument is more acceptable by farmers. Moreover, as the volumetric surface water pricing impedes reaching high abatement levels (and also higher income for farmers for this level of effort), the binomial tariff discount seems here the most interesting instrument.

Predictability

Quotas system performs best since it automatically reaches the targeted withdrawal level, whereas fees and surface pricing act in an indirect way (Figure 3Figure 3). Binomial tariff and fee system allow achieving intermediate withdrawal level as some dots are regularly plotted on their curves. Because a small shift in price could induce a sharp change in consumption (no intermediate withdrawals level between 50 000 and 10 000 m^3), the predictability of volumetric pricing is weak.

Figure 33: Impact of groundwater consumption on the income of a French vegetable producer.



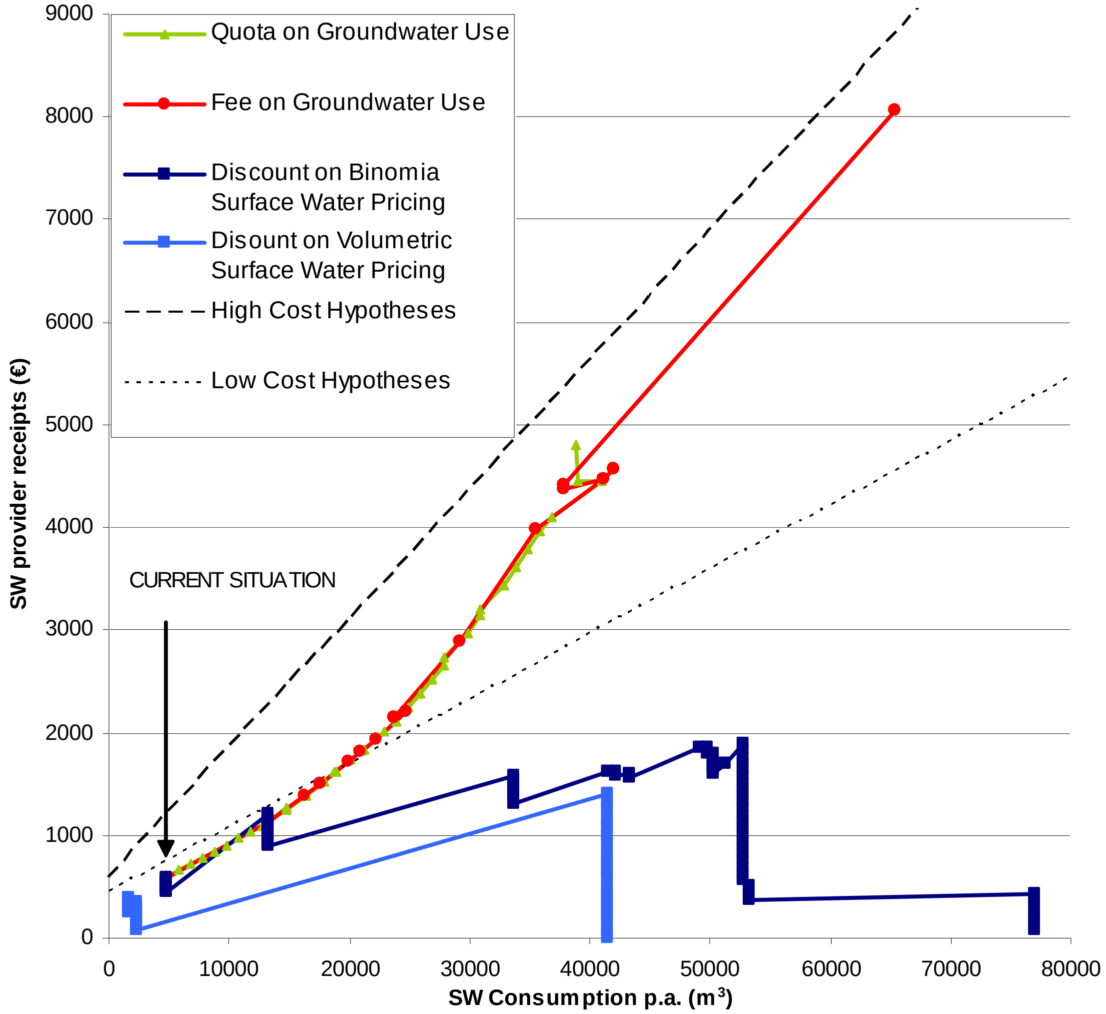
Additionally, a discount on binomial surface water pricing could conduct to adverse effects: surface and groundwater are substitutes in most cases, but they can act as complementary inputs. This phenomenon occurs for the second type of farmer (vegetable producer) (but not for type 1) on the right part of the binomial pricing curve (Figure 2Figure 2 and Figure 3Figure 3), i.e. beyond the "current situation" point: a small discount on surface water induces the farmer to grow water consumptive crops (i.e. artichoke). As the increase of surface water consumption is not sufficient to cover additional water needs, in term of delivered flow or water quantity, groundwater consumption increases. This phenomenon impacts negatively predictability.

Durability

Figure 4Figure 4 shows surface water supplier receipts according to surface water sold. We approximate further the cost faced by the supplier following a high and a low cost hypothesis (dashed curves). To do so, we assumed that the fixed cost supported by the supplier is delineated by its earnings ensuing from the "current situation" flow subscribed by farmers after the two tariffs proposed by the supplier. Besides, we consider that the variable cost is circumscribed by the two variable tariffs proposed by the supplier (see Table 1Table 1 for tariff levels).

In term of surface network sustainability (i.e. what we define here as durability), fees and quotas perform better than indirect instruments as the shift from ground to surface resource – at constant surface water price – increases supplier's earnings. Their implementation may apparently guarantee the network operation and maintenance costs to be funded at high surface water consumption as their curves are between the two cost hypotheses. Water pricing discounts – and firstly volumetric pricing – may conversely fail to guarantee cost recovery.

Figure 44: Surface water supplier receipts according to French vegetable producer's surface water consumption.



Implementability

To be considered as implementable, an instrument must follow regulations and laws, and implementation costs need to be at an acceptable level (less than the expected gain). The likelihood of the implementation of the proposed management tools depends first on the French and European legal frameworks and second on the implementation costs of the instruments which are related to the informational needs for their enforcement.

Legal Framework

The proposed instruments can likely be implemented in the French and European legal frameworks. First of all, water basin agencies exist, and put nowadays fees on water withdrawals and consumptions. Increasing the level of fees can then be a realistic option, even if maximal levels for water fees are nowadays directly put by the French water law.

The French legal framework allows also water quotas: the 2006 Water and Aquatic Environment Law introduces a new authority – the so-called "*Organisme Unique*" – focusing on collective management of irrigation water. Not implemented yet on the Roussillon floodplain, the *Organisme* will be in charge of:

- Gathering farmers' demand for irrigation water on a defined area.
- Asking to water authorities the multi-annual volume consumable by the whole agricultural sector on the area.
- Sharing the allocated volume between farmers.
- Defining rules in case of temporary water restriction or suspension.

Undoubtedly, the *Organisme Unique* management system seems to be a well-adapted legal framework for implementing quotas since it relies on a quantity-based mechanism.

An action on surface water pricing seems most difficult to implement. Following the cost recovery principle recommended by the WFD (Directive 2000/60/EC), it is difficult to imagine that a structure which have at least to balance its budget accept to loose money, only to save aquifer.

Informational costs

The information needed to implement groundwater management instruments can be costly. Direct instruments (fee and quota on groundwater) assume a perfect knowledge on groundwater users (registration) and their consumption (metering and control). Such information is still lacking in our case study since only 700 wells are registered over the about 3 000 the Roussillon floodplain may foster.

Indirect instruments do not suffer this shortcoming since the informational need focuses on farmers' behaviour toward surface water which is not an open-access resource. Surface water cannot be hijacked and uses are perfectly known and metered by the surface water supplier in order to apply the volumetric part of the pricing structure.

5.3. Summary and discussion

Table 3~~Table 3~~ summaries results by comparing the relative performance of the different groundwater management instruments taking into account the 5 criteria. It differentiates two cases, which represent two levels of abatement that authorities might be willing to reach: a low level of abatement and a high level one.

Table 3~~3~~: Groundwater management instruments relative performance relatively to the abatement level.

	Abatement level	Aggregate Income	Acceptability	Predictability	Durability	Implementability Legal Framework/ Informational Cost	Total
Quota on Groundwater	Low	.	.	+	.	+/-	++/.
	High	.	-	+	+	+/-	++/.
Binomial Surface water Pricing	Low	+	+	--	.	-/+	-/+
	High	+	+	-	-	-/+	-/+
Fee on Groundwater	Low	.	-	.	.	+/-	./--
	High	.	-	.	+	./-	./-
Volumetric Surface water Pricing	Low	+	+	--	-	-/+	--/.
	High	no	no	no	no	no	no

At low abatement level, surface water pricing instruments perform slightly better than groundwater based instruments in term of generated income, without conferring to them a decisive advantage. They additionally raise farmers' earnings, facilitating their acceptance by farmers. Outcomes of their implementation remain however uncertain since a small price change induces irregular shifts in groundwater consumption. Sensitivity of groundwater demand to surface and groundwater price signals imposes to the regulator to know perfectly farmers abatement cost and benefit functions in order to predict underground withdrawals accurately. Besides, the complementarity between resources could be encountered for vegetable producers leading to adverse effects.

Furthermore, surface water pricing discounts – and chiefly the volumetric one –impede the surface water supplier from generating sufficient receipts to cover operation and maintenance costs[5]. But surface water pricing discount are the only instruments which could be implemented at a low informational cost since groundwater consumption should neither be metered nor controlled. This finally advocates for a quota system as the theoretically most suited instruments for conjunctive use management in our case study.

This result still holds at high abatement level although quotas acceptance collapses as farmers income decrease. Notice once again that volumetric pricing structure fails to reach the targeted level and is thus not presented.

6. Conclusions

This paper aims at comparing several economic tools which may be implemented to mitigate current farmers' groundwater withdrawals in a conjunctive use context. A fined-tuned field work has been done with farmers to understand the key points of substitution between underground and surface water at the farm level. A linear programming framework has been used to model fruits and vegetable production systems. It shows that groundwater demand is sensitive to its cost.

Estimates of derived demand for irrigation water often conclude to short-term inelasticity (BONTEMPS and COUTURE, 2002), noticeably for farms using conservative irrigation technologies (VARELA-ORTEGA et al., 1998), at least up to a given threshold price level (GARRIDO, 1999). Unresponsiveness to price signals leads to the common statement of the ineffectiveness of price instruments for water conservation. In conjunctive use settings, substitution makes each resource sensitive to price signal although water consumption as a whole remains inelastic, legitimating deeper researches on price-based instruments.

In our case study, volumetric surface water pricing and fees on groundwater consumption however fail to satisfy our five criteria for instruments evaluation. We finally support the implementation of a quota system in our case study since it seems more adapted to the implementation of the "*Organisme Unique*" which introduces groundwater management based on consumable volumes.

Such a conclusion depends nevertheless greatly on the relative weight given to our criteria which ensues chiefly from political priorities of policy makers. Their inferences could be thus much different from ours.

Finally, quotas effectiveness – as for the other instruments – relies on information about withdrawers and their consumption that is still imperfectly known. This advocates for further researches on alternative management tools which might be effective even in an incomplete informational context.

[5] Our lack of knowledge about the costs faced by the supplier hinders us from being definitively affirmative.

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