Groundwater Management Instruments in a Conjunctive Use System: Assessing the Impact on Farmers' Income Using Mixed Integer Linear Programming (MILP)

Instrumente des Grundwassermanagements bei gemeinschaftlicher Nutzung von Grund- und Oberflächenwasser: Bewertung der Wirkungen auf landwirtschaftliche Einkommen mit einem gemischt-ganzzahligen linearen Optimierungsansatz

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Abstract

The objective of this paper is to compare the "relative" and the "absolute" impact on farmers' income of several economic instruments which may be implemented to mitigate farmers' groundwater withdrawals in a multi-resource system. We conducted fine-tuned field work with farmers in order to understand the key factors of substitution between underground and surface water at the farm level. A mixed integer linear programming framework has been used to model fruit and vegetable production systems and to infer the impact of instruments on farmers` income.

Assuming this impact will sharply influence the acceptability of the instruments by the agricultural sector, we demonstrate why farmers' acceptance is of central concern for both the design and the implementation of an environmental policy.
We further assessed the potential financial transfers that could be undertaken to increase acceptability. Our results echo scholars' doubts about the capacity of taxes to manage irrigation water use. We suggest that a policy relying on a "well-priced" substitutable resource would be greatly favoured by farmers and potentially by policy makers, since it will sharply decrease the transaction costs arising from the implementation of the instrument.

Key words

groundwater management; conjunctive use; irrigation; farmers' income; economic instruments; mixed integer linear programming

Zusammenfassung

In diesem Beitrag werden verschiedene Instrumente verglichen, die man zur Verminderung der Grundwasserentnahme durch Landwirte implementieren kann. Absolute und relative Wirkungen der Instrumente auf das landwirtschaftliche Einkommen werden gegenübergestellt. Wir führen eine empirische Untersuchung durch, die in Feinabstimmung mit Landwirten im französischen Roussillon-Tal erfolgt. Ziel ist es, die zentralen Einflussfaktoren für die Substitution zwischen Grundwasser und Oberflächenwasser auf der Ebene landwirtschaftlicher Betriebe herauszuarbeiten. Um die Effekte der Instrumente auf die landwirtschaftlichen Einkommen abzuleiten, wird ein gemischt-ganzzahliger linearer Optimierungsansatz verwendet, mit dem die Produktionssysteme der Obst- und Gemüseproduktion modelliert werden. Die Einkommenswirkungen der Instrumente bestimmen deren Akzeptanz im Agrarsektor, und deshalb ist die Akzeptanz von zentraler Bedeutung für die Ausgestaltung und Implementierung des auszuwählenden umweltpolitischen Instruments.

Außerdem werden mögliche finanzielle Transferleistungen analysiert, die zur Erhöhung der Akzeptanz bei Landwirten denkbar sind. Die Ergebnisse bestätigen die Einschätzung anderer Autoren, wonach die Besteuerung des Grundwassers zur Beeinflussung der Bewässerungsnachfrage nur wenig geeignet sind. Wir empfehlen eine Politik, die auf eine gezielten Steuerung der Preise des substitutiven Gutes – Oberflächenwasser – baut. Diese Politik würde von Landwirten bevorzugt werden und möglicherweise auch

von Politikern, weil sie die Transaktionskosten als Folge der Implementierung der Politik sehr stark senken würde.

Schlüsselwörter

Grundwassermanagement; Nutzung von Grund- und Oberflächenwasser; Bewässerung; landwirtschaftliche Einkommen; Instrumente der Wasserpolitik; gemischt-ganzzahlige lineare Optimierung

1 Introduction

The rapid rise in the population in coastal areas exacerbates conflict over the use of a limited resource, namely fresh water. This is particularly true in Mediterranean regions, where population migration, tourism and irrigation development create increasing pressure on water resources. Conflicts may then arise between users. This is the case notably for groundwater, which is a very attractive resource:

- It is often available at little depth, making it easy to extract (FORNÉS et al., 2005).

- It is often cheaper than surface water[1]: aquifers play the role of both reservoir and distribution network. Technological improvements have also greatly decreased extraction costs (LLAMAS and MARTINEZ-SANTOS, 2005). Conversely, surface water costs tend to increase for farmers: public financing programmes for irrigation are being reduced and there is an intention to apply a cost-recovery principle recommended in Europe by the Water Directive Framework (WFD).

- Groundwater quality is favoured by farmers as it is filtered by the substratum. It could even be potable if still pristine and can be directly used for drinking or precision irrigation.

- Groundwater is available on demand. Rotation constraints may exist in surface networks.

- Finally, groundwater is less subject to temporary withdrawal restrictions during droughts than sur-

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[1] Surface water is often cheaper than groundwater for farmers in gravity systems. Capital investment is, however, much higher. Some developing countries such as Algeria (IMACHE, 2008) or Jordan (CHEBAANE et al., 2004) subsidized individual access to groundwater rather than collective schemes to develop irrigation. There may be a conflict between the government's objectives of water preservation and irrigation development (IMACHE, 2008).

face water. Groundwater may be defined as a dynamic stock of water (KOUNDOURI, 2004) balancing water demand during dry periods. Since it diminishes the temporal scarcity of water, groundwater is highly valuable – compared to a stochastic surface water supply – for both tap water suppliers and irrigating farmers in arid or semi-arid contexts.

Consequently, farmers often abandon surface networks in favour of individual wells when both water resources are available. In conjunctive use systems, groundwater overexploitation may occur, even though an under-used surface water supply exists. Conjunctive management is therefore needed.

In their seminal paper, GISSER and SANCHEZ found that – provided the aquifer storage is sufficiently large – groundwater management is useless regarding social welfare (GISSER and SANCHEZ, 1980). Thus, few studies of conjunctive use systems focus on the implementation of economic instruments. NOEL et al. (1980) compare a quota and a tax system for groundwater consumption, while SCHUCK and GREEN (2002) study a supply-based water pricing structure of a conjunctive management system, defined as an area in which "surface supplies are managed jointly with groundwater resources" (SCHUCK and GREEN, 2002).

Since most multi-resource 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 resource are managed separately or not managed at all. In the latter case, surface and groundwater uses are in competition and the management of one resource may endanger the sustainability of the other. When addressing groundwater management instruments, too few papers take into account the substitution process that exists between water resources.

The neoclassical framework aims to compare natural resource management instruments by means of the efficiency criterion. Market-based instruments are often seen as more efficient than "command-and-control" tools, as they tend to reach marginal abatement costs, mainly when marginal abatement costs are heterogeneous across agents (STERNER, 2003).

Efficiency should not, however, be addressed as the sole criterion to assess water management instruments. Acceptance of public policy is of central concern too – chiefly when its implementation is in the agricultural sector – and this for two reasons: first, farmers are well-known for being influential regarding the political agenda; second, once a policy is selected,

its acceptance by stakeholders facilitates its implementation mainly by decreasing transaction costs.

The purpose of this article is to assess economic instruments that can be implemented in a multi-resource context from the farmers' viewpoint, i.e. without considering social optimality. Our research is based on a French case study: the Roussillon floodplain where two resources exist (groundwater and surface water). Surface water is distributed through a collective irrigation network, while groundwater is extracted through individual boreholes.

We assume the impact of instruments on farmers' income is a proxy for their acceptance by the agricultural sector. That is why we develop a microeconomic framework based on mixed integer linear programming (MILP) – and thus on income maximization – to model the irrigation decision process in a multi-resource context. In the present article, we first depict our case study and the management tools we aim to compare in section 2. In section 3, we demonstrate why focusing on farmers' acceptance is a key issue when addressing environmental policies in the agricultural sector. Section 4 describes our modelling approach and we present and discuss the outcomes of our models in section 5 before concluding in section 6.

2 Depiction of the Case Study

2.1 Agricultural Water Consumption in the Roussillon Floodplain: Presentation

The Roussillon floodplain is located in the extreme south of the French Mediterranean coastal region and lies over a two-layer aquifer. It is one of the driest areas in France: average rainfall is about 570 mm p.a., with high intra-annual and inter-annual variability. With the exception of vines, all the crops are irrigated.

The production of drinkable water (about 45 mill. m^3) relies exclusively on groundwater and constitutes the main use in terms of consumption. Groundwater is used routinely for agriculture (about 25 mill. m^3), with about 1 300 farmers extracting from individual wells (mainly from the shallow aquifer). To preserve the drinking resource, the authorities will limit the farmers' groundwater consumption by means of a so-called *volume prélevable*, the volume farmers are collectively allowed to withdraw from wells. Irrigated agriculture constitutes an important sector of the local economy and extraction abatement must first occur where substitution with surface water is possible (CG66, 2003).

We focus on the pressurized on-demand collective network of Villeneuve-de-la-Raho, whose water supply is secured by a 17.5 mill.m^3 under-used dam: the network spreads over more than 33.5 km² and could be extended to 52 km², while only about 12 km² are today cultivated with this water. This situation is explained by the presence of a free-access shallow aquifer underlying the whole area and competing surface water consumption. Like many other collective irrigation networks, the Villeneuve-de-la-Raho area constitutes, therefore, a conjunctive use system.

In this area, about 90% of the irrigated acreage is devoted to fruit (27%) and vegetables (62%) (AGRESTE, 2000). We identify two main types of irrigating farm on the area: the first type is specialized in orchards such as peach and apricot trees, while the second type grows vegetables like salad, potatoes or artichokes. Both irrigate with the help of water-conserving irrigation techniques (dripper or micro-sprinkler), the exception being artichokes (furrow irrigation). We limited the choice of crops because market access is particularly constraining in the area, limiting farm diversification.

Farmers point out that groundwater and pressurized surface water are perfect substitutes in term of satisfying the water needs of crops, because they allow the use of the same irrigation techniques. There are, however, three noticeable differences. First, pressurized systems deliver a higher and more flexible water flow. Second, the duration of irrigation can be enhanced with pressurized systems thanks to automation. Third, groundwater is cheaper than surface water once boreholes have been paid off.[2]

2.2 How to Manage Groundwater in a Conjunctive Use System? Description of Tools

Groundwater management policy can be inherited from different approaches:

- Coase's solution of privatizing the resource,
- Ostrom's solution of governing the commons,
- Hardin's Tragedy of the commons recommending access regulation,
- Pigou's solution of public ownership and the use of economic instruments.

By modelling the irrigation decision process and assessing the impact of groundwater management

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[2] This applies in our case study where most boreholes were dug during the 1970s.

policies at farm level, we focus on the last kind of solution.[3] Our aim is to identify economic instruments likely to be favoured by farmers in the Roussillon floodplain. In multi-resource contexts, as in the Roussillon floodplain, two types of management instrument for groundwater can be identified: direct instruments impacting farmers' behaviour towards groundwater, and indirect instruments impacting farmers' behaviour towards surface water and thus using the substitution between resources to manage groundwater extraction.

2.2.1 Direct Instruments

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

Taxes and Fees

Fees for water consumption already exist in France and are levied by the District Water Agency. This type of instrument allows us to consider all costs and benefits (and mainly the social ones) which are not taken into account by current prices: at an optimal level, it internalizes the externalities following the Pigovian framework. The difference between tax and fee deals with the final destination of fiscal receipts: fees for water use are collected to fund specific water preservation or improvement activities (combating water pollution, increasing the supply or subsidies for practice change), and taxes go to the general state budget, without any specific destination.

Quotas

Quotas belong to quantity-based instruments. A quota imposes an upper limit on water consumption and can be specified using volumetric, discharge or time units (possibly combined) (MONTGINOUL, 1998) and can be supplemented by technology standards (on the depth and the location of boreholes, the type of pumping equipment, etc.). In this paper, we test the implementation of volumetric quotas with two different scenarios:

- Quotas allocated on the basis of the acreage owned by farmers.
- Quotas allocated on the basis of past consumption, i.e. a grandfathering process.

2.2.2 Indirect Instruments: Surface Water Pricing

Multi-resource systems offer alternative management options. As surface water is a substitute for groundwater, surface water pricing impacts groundwater consumption. Recalling the Indian "energy-irrigation nexus" (SHAH et al., 2004; KUMAR, 2005), we might imagine a "surface water-groundwater nexus" able to manage indirectly resources thanks to pricing level and structure.

We compare a discount on two surface water pricing structures, taking into account the delivery constraints of the surface network:

- A binomial pricing structure with a fixed part proportional to the subscribed flow.
- A purely volumetric tariff with a constrained subscribed flow.

3 On Acceptability by Farmers in the Roussillon Floodplain

The assessment of the impact of management tools on farmers' income provides an insight into the acceptance of those tools by the agricultural sector.[4] This acceptance is of central concern, chiefly in the French context, and is likely to impact *ex-ante* the policy building process by orienting authorities toward a specific policy, and *ex-post* by facilitating its implementation. We first describe these two impacts before defining the two dimensions we include in acceptability. We finally present what we expect in terms of the acceptability of instruments.

3.1 The *ex-ante* Impact of Acceptability by Farmers

According to public choice theory, political leaders and bureaucratic administrators take into account the interests of agents subjected to environmental management instruments as well as agents affected by externality before shaping a public policy (BUCHANAN and TULLOCK, 1975). The two main populations affected by groundwater management are farmers and tap-water consumers. The relative influence of a population on a policy process is linked to its size, its rate of mobilization, its preference intensity and its pivotal position (ELLIOTT and HEATH, 2000).

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[3] A quota system could be seen as a privatization tool guaranteeing *usus* and *abusus* to farmers. Guaranteeing *fructus* would involve tradable water quotas.

[4] It must be underlined that acceptability cannot be seen as a financial issue only.

3.1.1 Group Size and Mobilization Rate

Tap-water consumers represent the quasi totality of the population and their electoral impact is potentially much larger than that of farmers. However, they constitute a typical "latent group" in keeping with the Olsonian framework: they are too large to avoid the free-riding problem (OLSON, 1971). Conversely, smaller groups tend to be politically more successful. Unsurprisingly, agricultural interests are highly mobilised (ELLIOTT and HEATH, 2000) thanks to a membership density favouring farmers' disproportionate clout (KEELER, 1996).

Our case study provides a good example of farmers' mobilization about water issues. In 1993, the District Water Agency identified about 30 farmers from the Roussillon floodplain who extracted groundwater without paying fees for their consumption. After evaluation of their consumption, the District Water Agency presented a 10-year consumption bill to offenders, provoking an outcry within the local agricultural sector. The offenders organized themselves in an irrigators' union. Although they have had to pay fees on their groundwater consumption since 1993, they eventually succeeded in not paying the 10-year bill, which was in fact covered by the local authorities.

3.1.2 Preference Intensity

Mobilization of agents depends greatly on the scope of a policy in their daily life. Irrigating farmers may have a lot to gain from influencing the choice of a water management policy. Water constitutes an important input in irrigating farms, mainly where rainfall is scarce and the water needed by crops comes mostly from irrigation, as in the Roussillon floodplain where 93% of the equipped areas were irrigated in 2000 (AGRESTE, 2000). Implementing tools to manage groundwater withdrawals may then sharply affect farmers' income. Moreover, it leads to a loss of competitiveness because water policies are implemented at the hydrogeographic level, whereas competition on food markets is international. Thus, farmers' preference intensity for water policy is high.

Conversely, the share of water in total expenditure is extremely low for tap-water consumers: on average water bills represented 2% of the annual household income declared to fiscal services in 2006 in the department *Pyrénées Orientales* (MONTGINOUL, 2008). The level of water bills plays, therefore, only a minor role in their consumption, since water costs can be incorporated in an individual's accommodation expenses and meters can be collective. Thus, tap-water consumers' preference intensity is low.

3.1.3 Pivotal Position

Farmers represent the ultimate "insider group" (ELLIOTT and HEATH, 2000)[5] and their political clout remains far above their demographic weight. For instance, 18% of French mayors were farmers in 2001, whereas they account for less than 3% of the active population (according to the *French Mayors' Association*). Since farmers constitute an "insider group" with an interest in getting involved in the debate, we expect their acceptance to orientate policy makers toward a specific water policy.

3.2 The *ex-post* Impact of Acceptability by Farmers

Once a policy has been selected, its acceptance by stakeholders eases its implementation. Environmental policies induce non-neglectable transaction costs such as bargaining, administrative, compliance or enforcement costs. The full acceptance of a policy may reduce those transaction costs, since negotiation, controls and information gathering processes would be facilitated. For instance, in our case study, of the estimated 3 000 wells in the Roussillon floodplain only about 700 were registered in 2005, and about 130 possessed a meter. This lack of information is mainly due to the low acceptance by farmers of the management tools currently proposed by water managers.

3.3 Twofold Acceptability: Absolute and Relative Dimensions

The *self-interest hypothesis* suggests that people are motivated by their own utility level. There is plenty of experimental or empirical evidence to suggest that individual preferences are not disconnected from the utility of others in either a positive (fairness, altruism) or a negative way (envy, jealousy) (SOLNICK and HEMENWAY, 1998; ZIZZO and OSWALD, 2001; BECKMAN et al., 2002; BAULT et al., 2008; ABBINK et al., 2009; CELSE, 2009). Scholars incorporate both effects in the concept of interdependent preferences. LOEWENSTEIN et al. (1989) find robust evidence of a strong aversion to disadvantageous inequity among players comparing their pay-off with a reference person (LOEWENSTEIN et al., 1989). This aversion is strongly influenced by social proximity (FEHR and

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[5] An "insider group" can be defined as "*a group pursuing non-controversial aims through bargaining between officers and public servants and adhering to 'rules' of bargained incrementalism*" (GRANT and DARREN, 2003).

SCHMIDT, 1999) – which is important among the farmers of the Roussillon floodplain.

Negative interdependent preferences (inequity aversion, envy) may incite agents to undertake actions that reduce others people's income even if those actions are costly (CELSE, 2009). Thus farmers might be more active in resisting an environmental policy if it seems to them to be inequitable.

Studying bargaining models, BOLTON (1991) states that, although pay-off is "*the only commodity involved in negotiations, bargainers act as if there are two: absolute and relative money*" (BOLTON, 1991). Thus, in order to assess groundwater management instruments, we define the "absolute" and the "relative" acceptability of a policy: the former means that a policy is accepted by an agent if it does not decrease his income, while the latter means that a policy will be more acceptable if it impacts agents' earnings equally.

3.4 On the Acceptability of Groundwater Management Instruments

In the Roussillon floodplain, for decades groundwater as drinking water has had priority over irrigation (CG66, 2003). The scope of farmers' influence is thus not whether a groundwater management policy must be adopted or not, but rather which policy instruments should be implemented.

It is well known that taxes provoke reluctance. BUCHANAN AND TULLOCK (1975) explain the relative rareness of implementing market-based instruments – compared with command and control instruments – as the result of firms lobbying for the latter. This is due to the negative impact on firms' profits that market-based instruments have compared with command and control instruments. Although most farmers from Roussillon are opposed to the implementation of management instruments, they are more receptive to a quota system than to fees for groundwater (49% for quotas and 8% for fees) (MONTGINOUL and RINAUDO, 2009).

We expect quotas to impact farmers' income less than taxes and fees, since they do not capture the rent that farmers have by exploiting the aquifer. Conversely, indirect instruments may increase farmers' income by decreasing the surface water price. However, we have no idea what the absolute income losses (or gain) experienced by farmers are and how those losses are influenced by the intensity of reduction of groundwater consumption.

A tax on fossil energy has been recently rejected by a referendum in Switzerland. However, how the levied taxes were to be redistributed influenced the vote: a smaller tax, with revenues earmarked for a wide range of subsidies – inducing financial transfers – was favoured over classical taxes (THALMANN, 2004). We will further focus on the potential financial transfers that could be undertaken to raise acceptability.

The impact of instruments on income is linked to the elasticity of groundwater demand. With a low elasticity of groundwater demand, the impact of a tax on a farmer's income will be high: farmers will not decrease their groundwater consumption by much, while costs associated with irrigation will increase. Groundwater demand elasticity depends on the spectrum of management options the farmer has: changes in irrigation techniques, on-farm water management, crop selection, cropping patterns, irrigated acreage or the water resource (VARELA-ORTEGA et al., 1998; WILLIS and WHITTLESEY, 1998).

Substitution between water resources may thus facilitate the acceptance of groundwater management instruments. So we need to develop a model that takes accurate account of the substitution process between surface and groundwater.

4 Model Description

4.1 Methodology Used

We adopt a particular case of linear programming: MILP. Linear programming has been used for decades in agricultural production economics (BOUSSARD and DAUDIN, 1988). It states that farmers maximize their individual income through the optimal combination of inputs, crops and acreages under economic, agronomic and technical constraints. The relationship between input and output is given by a set of fixed coefficients.[6]

Mathematical programming has frequently been used by scholars to address groundwater extraction issues. Most recent papers have combined economic models with hydraulic, hydrogeological or agronomic models (WILLIS and WHITTLESEY, 1998; PULIDO-VELAZQUEZ et al., 2004; SCHOUPS et al., 2006; MONTAZAR et al., 2010). Others consider domestic or

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[6] Non-linear programming frequently used to model irrigation decisions relaxes additivity and/or proportionality hypotheses. We assume additivity holds for water quantities applied to crops: surface and groundwater are assumed to be perfect substitutes. Proportionality can be relaxed using crops' water response functions. Such a function would be convex for the studied crops and can be approximated with fixed coefficients.

industrial water demand (PULIDO-VELAZQUEZ et al., 2006). Our model does not attempt to achieve this scope. Its originality lies in the fine-tuned field work carried out with farmers to determine the substitutability of both surface and groundwater. This allows us to infer the impact of economic instruments on production systems. We recall that we are looking neither for the social optimum nor a special instrument implementation level, but rather for the impact of the instruments on farmers' income according to different abatement levels of their groundwater consumption.

4.2 Optimization Process

Our model relies on the static optimization (1) of farmer's annual profit (Π), expressed as the sum over crops of annual per hectare net benefit (NB_c) multiplied by the acreage grown (X_c) minus the per annum total water expenditures according to resources (WC_r) and labour cost (LC) (variables and indices given in table 1). We assume farmers to be risk neutral. We divide the year into 24 equal periods (p) as labour and water needs are typically seasonal.

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

4.3 Water Equations

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

(2) $WC_r = FC_r + (VC_r + FEE_r) \cdot WQ_r$

(3) $FC_r = FIX_r \cdot FLOW_r$

The current structure of surface water pricing is binomial with a fixed part proportional to the subscribed flow and giving a free water allocation and a volumetric part once the free allocation is exhausted. Two tariffs for farmers are proposed (table 2).

Optimization is further constrained by:

- A periodic water need constraint (4): periodic water needs ($WN_{c,p}$) (table 3) are satisfied by rain ($RAIN_p$) and applied water quantity ($WQ_{r,p}$) from different resources.

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

- A water delivery constraint (5): periodic water needs should be covered by the sum of resource delivery flows ($FLOW_r$) multiplied by the duration of irrigation (ID_r). This guarantees that the needs are covered even if periods of no rain occur.

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

4.4 Labour Equations

Our model takes account of seasonal and permanent labour costs (6) which equal the sum of all labour inputs (SL_p, $PL \cdot PLA$) multiplied by wages (SLW, PLW) (7) (8).

(6) $LC = SLC + PLC$

(7) $PLC = PLW \cdot PL \cdot PLA$

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

Table 1. List of Variables and Indices

Variable	Description	Features
X_c	Acreage grown	Positive
WQ_r	Water quantity per year	Positive
$FLOW_r$	Water flow	Positive, mixed integer
PL	Permanent labour	Positive, integer
SL_p	Seasonal labour	Positive, integer

Indice	Description
c	crops
p	15 day period
r	water resource

Source: authors

Table 2. Water Cost Variables for Surface Water (SW) and Groundwater (GW) (U = per m³)

SW	FIX	VC	FEE
Tariff 1	74 € U/h	0.063 € U	0.009 € U
Tariff 2	55 € U/h	0.126 € U	

GW	FIX	VC	FEE
	10 € U/h	0.03 € U	0.0075 € U

Source: authors

Table 3. Annual Water Needs by Crop

Crop	Salad	Potatoes	Apricots	Early peaches	Peaches	Artichokes
Annual water need (m³/ha)	1 350	3 320	4 050	6 110	6 680	14 600

Source: authors

Permanent tasks are carried out by permanent workers and family members 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) $\Sigma_c \, PLN_{c,p} \cdot X_c + RPL_p \leq FLA + PL \cdot PLA$

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

4.5 Land Constraints

Finally, land constraints are 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 crop acreages (X_c), water consumption from each resource (WQ_r), water flow subscribed to the surface water network or the pumping capacity from wells ($FLOW_r$), and permanent and seasonal workers hired on-farm (PL and SL_p).

We run our model over different seasons to address inter-annual rainfall variability and its impact on farmers' behaviour. Wet, mean and dry years are computed with a 30% deviation from average rainfall calculated with data over the period 1971-2008. Intra-annual variability is addressed via the multi-periodic structure of the model. We observe that the sensitivity of the model to rainfall remains low, as dry, mean and wet year data produce relatively similar outcomes. This explains why we have not introduced farmers' risk attitude regarding rainfall. According to local specialists, the outcomes of our model for a mean year appear to be close to reality. They are displayed in table 4.

4.6 Implementation of Instruments

The different types of instrument presented in section 2.2 are tested: quotas and fees for groundwater and discounts on binomial and volumetric surface water pricing. Technically, they are integrated in our model as follows: quotas for groundwater are incorporated by adding a volumetric constraint on water quantities withdrawn from wells; fees for groundwater and surface water pricing instruments are introduced into equation (2).

The 2006 French water law introduced the concept of *volume prélevable* ("withdrawable volume") defined as the total volume that farmers can collectively withdraw from the aquifer. We assess the instruments, looking first at the individual level according to the groundwater consumed by farmers, and second at the aggregated level for four implementation levels of the *volume prélevable*.
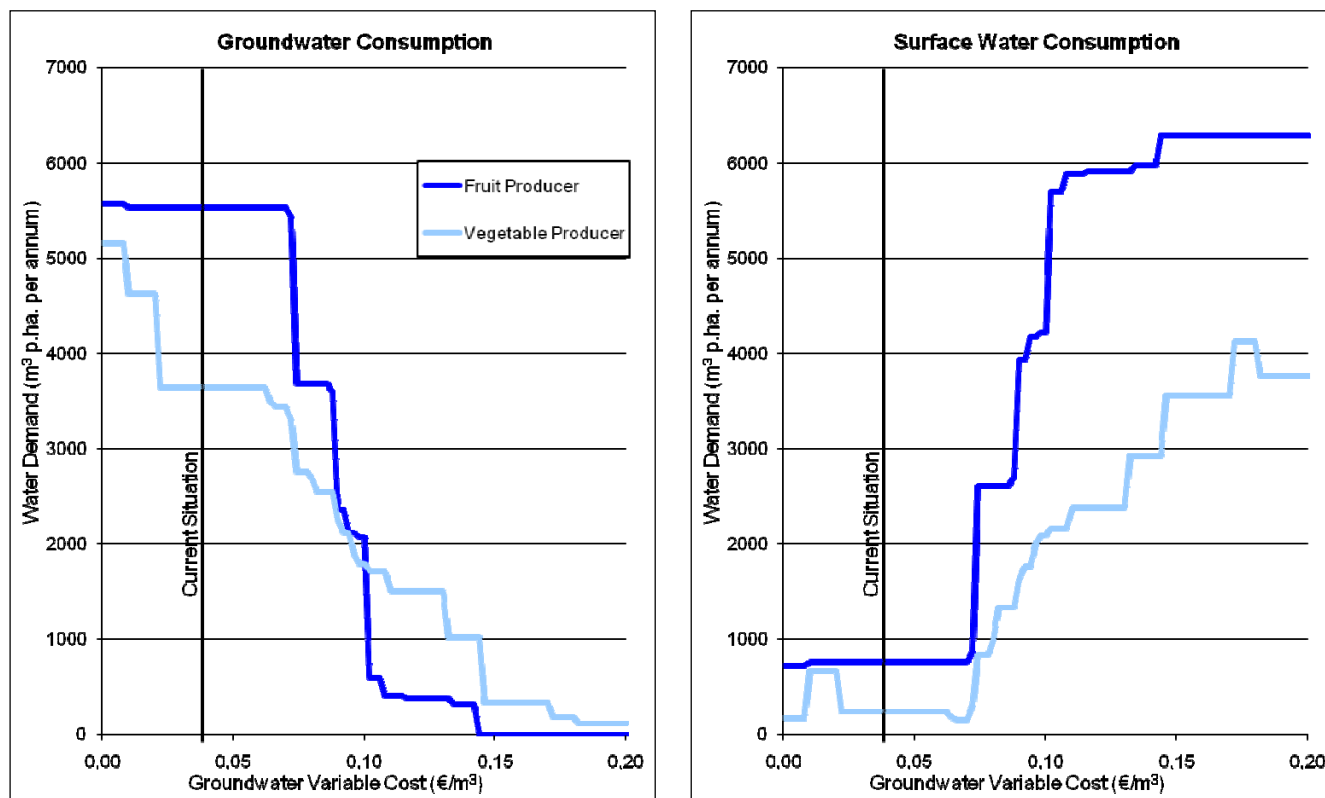
5   Results

The results presented in this section deal first with the shape of water demand curves derived from our model. We then display the outcomes of the different management instruments in terms of both "relative" and "absolute" acceptability before evaluating the financial transfers that could be undertaken to enhance acceptability by farmers.

5.1 Responsiveness of Groundwater Demand to Price Signals

Estimates of derived demand for irrigation water often conclude that there is short-term inelasticity (BONTEMPS and COUTURE, 2002), noticeably for farms using water-conserving 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-based instruments for water conservation and many authors are cautious about the helpfulness of water pricing for water management, arguing that no real-world case of successful water pricing management has yet been documented (CORNISH et al., 2004).

Figure 1 presents the short-term water demand curves per hectare of both farm types. Groundwater demand is highly sensitive to the variable extraction cost of groundwater (pumping cost, fees, etc.). Its decrease is mostly balanced by the rise in surface water consumption: in conjunctive use settings, substitution makes each resource sensitive to price signals

Table 4.   Main Features of Farm Types

Farm Type	Fruit producer	Vegetable producer
Area	20 ha	10 ha
Familial labour	1 person	1 person
Crop distribution	Early Peaches: 52%	Artichokes: 7%
	Peaches: 36%	Salad: 45%
	Apricots: 12%	Potatoes: 85%

Source: authors' computation

Figure 1.   Per-hectare Water Demand of both Farm Types

Source: authors' computations

– although water consumption as a whole remains greatly inelastic. This demonstrates the potential effectiveness of a groundwater management policy that relies on price-based instruments targeting surface and/or groundwater.

We estimate the current groundwater extraction cost to be about 0.03 €/m³, while the fee currently levied by the District Water Agency is 0.0075 €/m³. The "current situation" is thus located on the flattest part of the groundwater demand curves, while the substitution process occurs only at a higher cost level (0.06 to 0.07 €/m³) corresponding to the variable price of surface water: groundwater demand is inelastic around the current situation.

5.2 Comparison of Instruments

5.2.1 At the Individual Level

Figure 2 displays the impact of each instrument on the income of both farmer types according to different instrument levels. It reveals the "relative" acceptability of the instruments, for a given implementation level.

If direct instruments decrease farmers' income up to 10%, their impact on the two farm types differs. Fruit producers' income appears to be more impacted

than that of vegetable producers due to the relative inelasticity of their groundwater demand compared with the vegetable producers. This ensues from the narrowness of the spectrum of their management options (fixed acreage). The "relative" acceptability of grandfathered quotas is shown to be higher, since the difference in income between both farm types is lowered. It appears to be a rather egalitarian instrument.

Binomial surface water pricing increases farmers' income without any difference between both farm types and can be seen as the most equitable tool. The volumetric surface water tariff raises farmers' income too, but conversely its impact differs after a given price level (0.03 €/m³).

5.2.2 At the Aggregated Level

Figure 3 displays the total income of the fruit and vegetable producers according to different levels of groundwater consumption abatement at the irrigation scheme level. This corresponds to the different restriction intensity induced by the implementation of the *volume prélevable*. Aggregation using the two modelled farm types is imprecise and values at the aggregated level should be treated with caution and regarded as insights rather than precise estimates.

Figure 2. **Variation of Farmer's Income – at the Individual Level – for Different Instruments and Instrument Levels (current income = 100)**
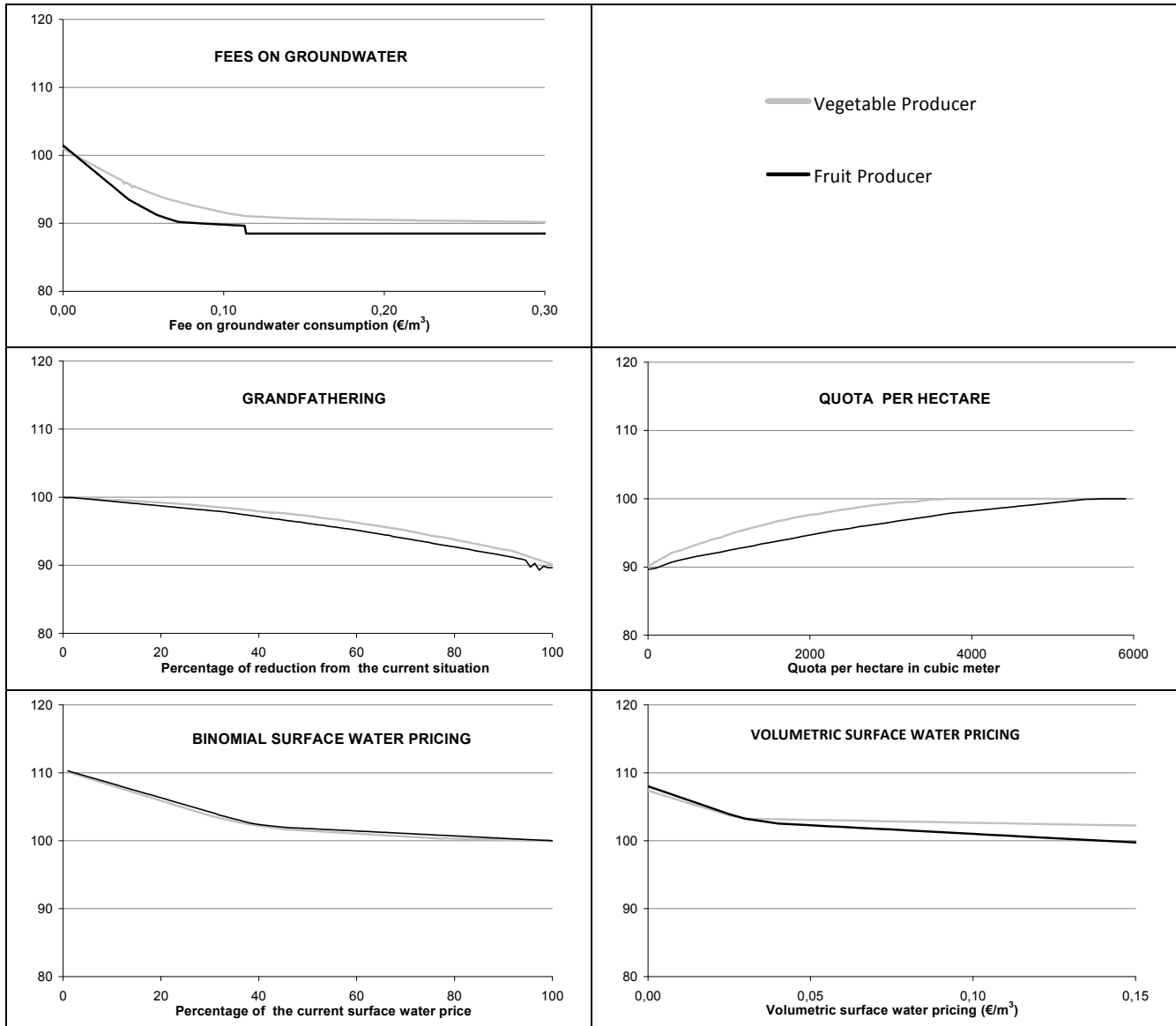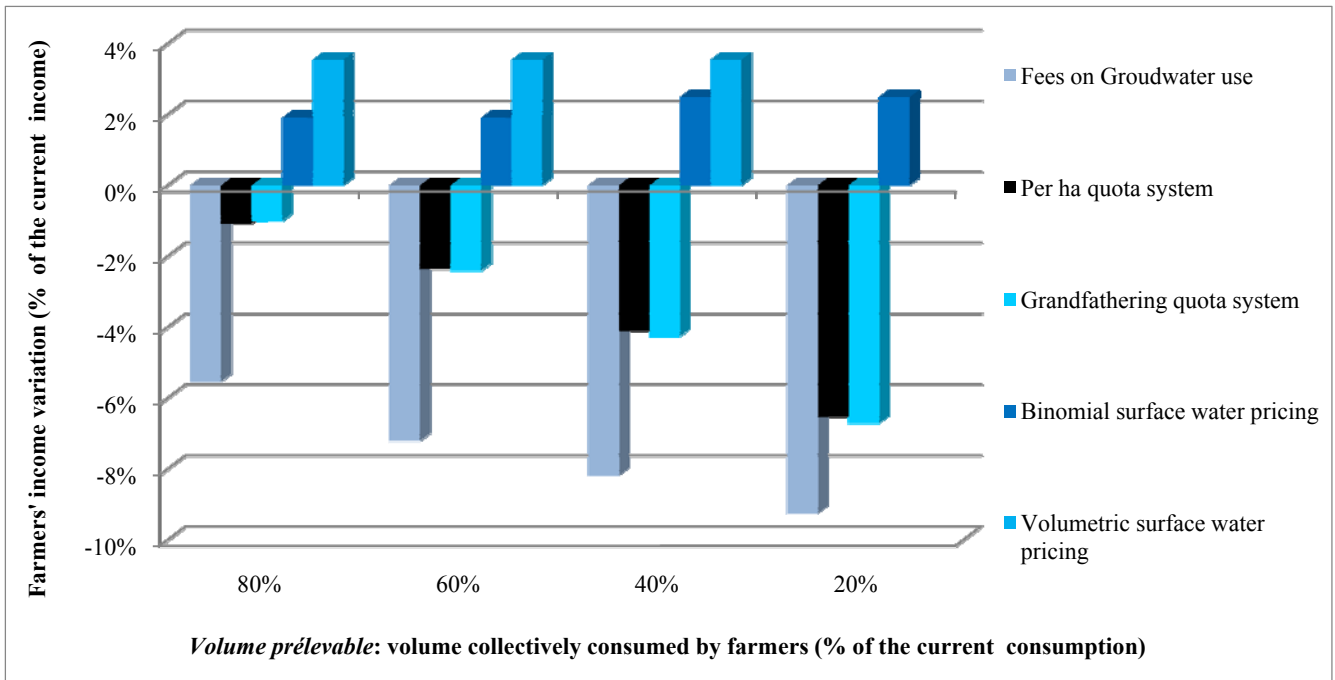

Source: authors' computations

When imposing a reduction in groundwater withdrawals, fees and quotas for groundwater decrease the sector earnings. Fees sharply reduce farmers' income at the early abatement level while quotas act in a more steady way. The difference between quotas and fees is mostly captured by the District Water Agency. The two instruments finally converge at high abatement levels and decrease sector earnings by up to 9 % and 7 % respectively. CORNISH et al. (2004) estimate that expenditure on water must amount to about 20% of farmers' net income before it has a significant impact on water use. The sensitivity of groundwater demand ensuing from the substitution process means in our case that farmers bear a slightly lighter burden.

As shown in section 5.1, groundwater consumption remains unresponsive to an increase of the fee level until a given intensity of the price signal. To reach a 20% abatement, fees have to be raised to $0.04 €/m^3$ compared with the current $0.0075 €/m^3$. This level is above the maximal level fixed by the 2006 French Water Law ($0.03 €/m^3$) which would, therefore, not induce much change in terms of groundwater withdrawals (see figure 1). This corroborates the following statements that:

- Fees are designed to fund water authorities' financial activities rather than to reach the optimal desired level of groundwater consumption (DA MOTTA et al., 2004).

Figure 3. **Impact of Groundwater Consumption on the Income of the Agricultural Sector**

Volume prélevable: volume collectively consumed by farmers (% of the current consumption)

Source: authors' computations

• Increasing the price signal is not an easy way of reducing irrigation water use (CORNISH et al., 2004).

The agricultural sector may prefer a discount on surface water, because it increases its income (up to 4% with volumetric pricing). We conclude that indirect instruments are more likely to be accepted by farmers.[7]

5.2.3 The Transfer Issue

The acceptability of environmental management instruments can be enhanced thanks to financial transfers from public authorities to stakeholders (THALMANN, 2004). Such transfers can only be justified if social welfare increases after the implementation of a given instrument. This is chiefly the case with fees, since they are theoretically more likely to induce larger social benefits than command and control instruments, and they are levied to fund environmental protection measures such as subsidies for changes in agricultural practice.

Financial transfers are discussed less frequently in the case of a quota system, because authorities do not receive any financial resources from its implementation. However, in our conjunctive use context the

District Water Agency still levies fees for ground and surface water. As surface water consumption increases with the decrease of groundwater extraction – and thus with the decrease in farmers' income – financial transfers from the District Water Agency to farmers should be taken into account.

Figure 4 displays the potential for financial transfer from the District Water Agency to the agricultural sector, calculated as the percentage of the agricultural sector's income loss that can be borne by the increase in the Water Agency's earnings compared with the "current situation".

It is no surprise that the fee system provides the highest potential for financial transfers. The additional earnings of the District Water Agency could cover between roughly 15% and 60% of the agricultural sector's losses. If implemented, financial transfers could sharply increase the acceptability of fees for groundwater consumption.

The introduction of a quota system allows the District Water Agency's earnings to cover between 2% and 4% of the agricultural sector losses over a large range of the abatement spectrum. At low abatement levels (20% of reduction), grandfathered quotas fail to provide additional financial resources to the District Water Agency. Farmers' income losses are, however, relatively small (up to 1%) at this level of reduction (see figure 3). Whatever quota system is adopted, financial transfers would remain quite

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[7] Due to the limitation in terms of subscribed flow to the surface water network that we introduced in 2.2.2, volumetric surface water pricing fails to achieve the highest groundwater consumption abatement levels.

Figure 4. Potential for Financial Transfer from the Water Agency to the Agricultural Sector

Volume prélevable: volume collectively consumed by farmers (% of the current consumption)
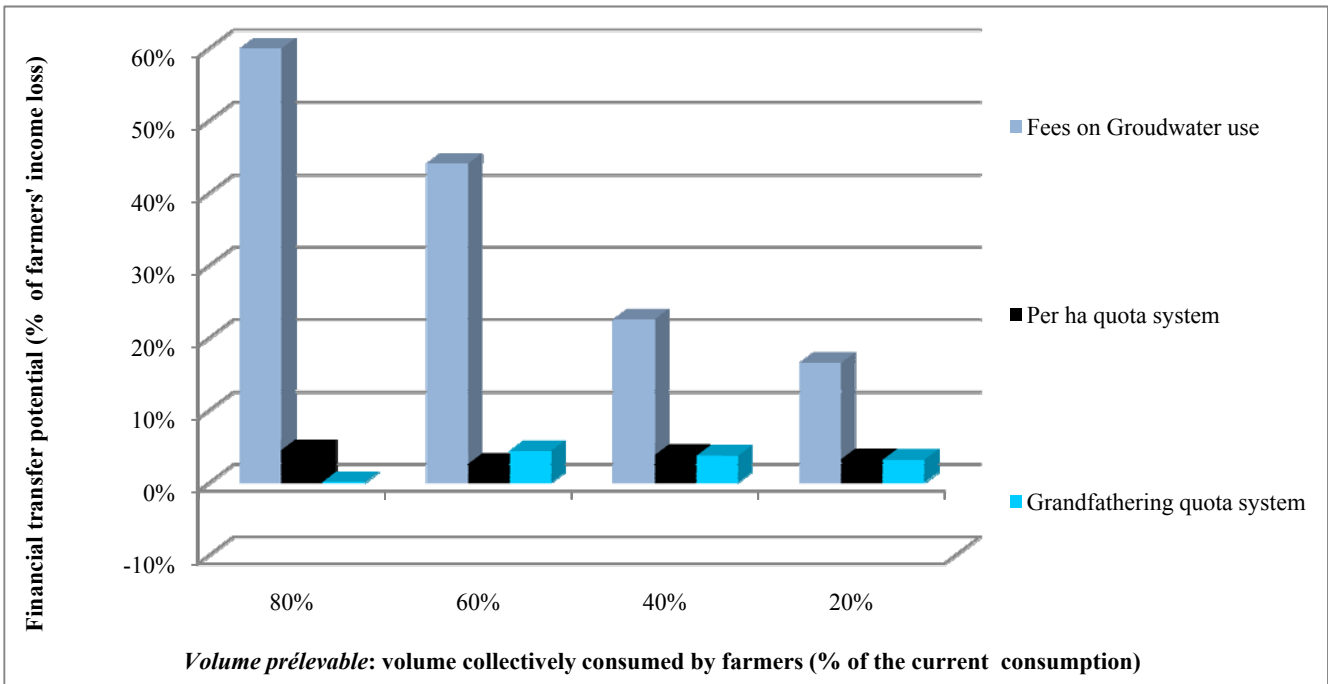
Source: authors' computations

limited. The District Water Agency could only undertake targeted measures such as bridging the gap between the incomes of both types of farmer and thus increasing the relative acceptability of quotas.

5.3 Summary and Discussion

Figure 5 synthesizes the relative performance of the different instruments in terms of acceptability. A fee system is the least acceptable instrument in absolute terms and performs weakly in relative terms. It does create, however, the highest potential for financial transfers. The agricultural sector might therefore contest its selection by public authorities and, if chosen as a management tool, impede its implementation, but it would benefit from the levied fees in the form of a financial transfer. Such a scenario would generate high transaction costs for both the agricultural sector

Figure 5. Performance of Instruments according to the two Dimensions of Acceptability
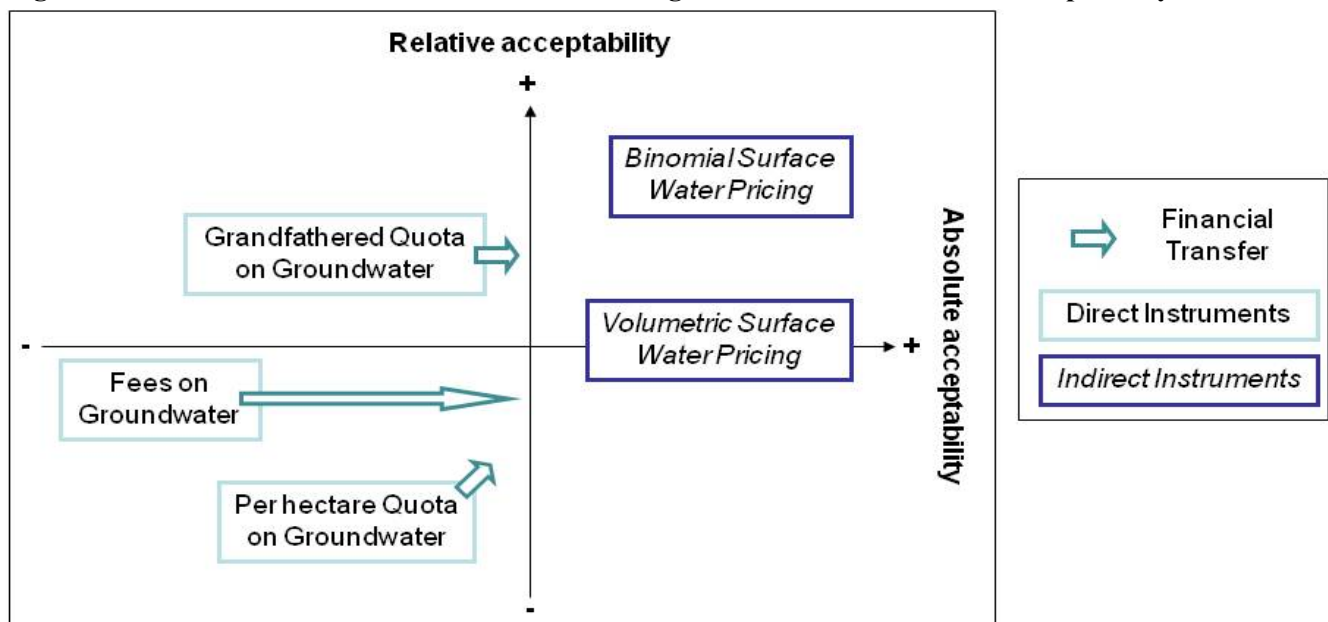
Source: authors

and public authorities. A long-run bargaining process would be needed to design the policy (fee level, transfer amount and distribution) and to enforce it (adoption of meters).

Even in a multi-resource system – where groundwater demand is more elastic than in a non-conjunctive use setting – taxes set at an "acceptable" level seem ineffective as a way of managing the resource: they decrease farmers' income strongly without reducing groundwater demand. The substitution process is not sufficient to induce conjunctive management through taxes in our case study.

Quotas are "absolutely" more acceptable than fees. They create, however, low-level capacity for financial transfer, limiting the scope of corrective measures that could be implemented to increase acceptability. A quota system would, therefore, give rise to fewer transaction costs, first because farmers' opposition would be lowered compared with fees, and second because transfers would be limited. However, the way of allocating quotas to farmers impacts the "relative" acceptability and would thus be subject to negotiation.

Indirect instruments – decreasing the cost of irrigation with surface water – enhance farmers' income. Interestingly, the higher the groundwater consumption abatement level, the higher the farmers' income. They perform, therefore, better in terms of absolute acceptability.

In terms of relative acceptability, binomial surface water pricing is the best management tool assessed, while the volumetric tariff would apparently be favoured by vegetable producers at low abatement levels. Thus, the former structure might be adopted more easily by farmers. Implementation costs would be dramatically decreased, since neither negotiation nor financial transfer would be undertaken. Furthermore, a discount on the binomial surface water tariff does not involve any enforcement costs, since no metering systems are needed for groundwater.

Conjunctive management seems possible via a discount on the current binomial surface water pricing. Two problems arise, however, which have to be solved: (i) the cost recovery of the surface water irrigation scheme needs to be guaranteed, and (ii) the supply of the substitutable resource must be consistent and secured.

6 Conclusions

The aim of this paper is to compare from the farmers' viewpoint different economic tools that may be implemented to mitigate farmers' groundwater withdrawals in a conjunctive use context. Fine-tuned field work was conducted with farmers from the Roussillon floodplain in France to ascertain the key points of substitution between underground and surface water at the farm level. We model fruit and vegetable production systems with the help of an MILP framework.

The results of our simulations suggest that in a conjunctive use system the elasticity of farmers' short-term groundwater demand is artificially enhanced by the substitution occurring between water resources. However, the production systems we examine – based on orchards and vegetable crops – remain unresponsive to the commonly used level of fee. The substitution process seems insufficient to induce conjunctive management with direct price instruments. Financial transfers might provide improvements, but they will give rise to high transaction costs.

The quota system performs better in that it imposes the desired water consumption level. It still decreases farmers' income. Financial transfers remain limited and would not increase the "absolute" acceptability by very much. The way of allocating quotas further impacts their "relative" acceptability. Farmers would negotiate both the quota level and the allocation process, thus increasing transaction costs.

Taxes and quotas seem ineffective to manage water from the farmers' viewpoint. There is a need for other economic instruments or even management approaches. Conjunctive use systems create a great management opportunity for groundwater: changing the pricing structure or the pricing level of substitutable resources impacts groundwater consumption. In our case study, a discount on the current binomial surface water pricing would be favoured by the agricultural sector, since it ensures both relative and absolute acceptability. Consequently, it would sharply decrease the transaction costs associated with its implementation. The supply of the substitutable resource must be consistent and secured, while the cost recovery of the surface water irrigation scheme remains an open issue.

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