Controlling Households' Drilling Fever in France: an economic modeling approach

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ABSTRACT

This paper describes an unintended negative environmental impact of water price increase in the drinking water sector. Using primary data collected at the national and local levels in France, it shows how water price increase, initially intended to generate environmental benefits through reducing water use, has produced economic incentives for households to drill their own garden boreholes. The development of such boreholes is now causing major pollution risk for groundwater in urban areas. It also represents a major source of management problem for public water utilities. The paper first presents the results of a national survey which identifies the increasing number of garden boreholes as an issue of concern in a majority of the French counties. The motivations of households installing a tube well are then investigated though individual interviews in a local case study. The factors determining the decision to invest in a tube well are identified and a micro-economic model representing the decision process is developed. This model is used to assess the probability of development of private boreholes on a regional scale, under different economic scenarios.

Keywords: groundwater; economic modeling; France; households; domestic boreholes; tube well; water pricing.

I. INTRODUCTION

During the last three decades, the use of economic instruments – taxes, pricing and water markets - has been increasingly advocated as an effective solution to reduce water use and abstraction, and to protect water resources from over-exploitation and degradation [*Briscoe*, 1997]. In Europe, this new approach of water resources management is reflected in recent policy orientations taken by the European Commission and by several Member States and Accessing Countries [*European Commission*, 2000; *Hrovatin and Bailey*, 2001]. It is also reflected in the level of water prices which have been rising significantly in real terms, as shown by the comparative study carried out by OECD in 1999. Annual rates of growth in water and sanitation charges over recent period ranging from five to seventeen years were assessed for thirteen European countries (and other non European). In five countries, price increases were at least four percent and in another eight countries between two and four percent per year [*Herrington*, 2001; *OECD*, 1999].

The case of France, where the average drinking water price rose by seven percent per year on average between 1991 and 1997 perfectly illustrates that trend [*DGCCRF*, 1999]. Statistical data suggest that this price increase has been concomitant with a reduction in water consumption. The average water consumption of French households, which had continuously increased from 106 liters to 161 liters per person and per day between 1975 and 1991 stabilized in the early 1990's and slowly decreased afterwards. This trend reversal has been attributed to the sharp increase of water price. It is assumed that water customers have cut down their water purchase after water rates were increased, with impact noted in the short run (a few weeks or months) and long run (multiple years). Over short time periods, households have first decreased water uses they value least (outdoor uses such as car washing or garden watering), reduced leakage losses (taps, etc) and changed consumption habits (duration of showers and frequency of baths, etc.). Over longer time periods, households are assumed to have installed water saving appliances and devices (low flow toilet flushes, adjustable shower rose, etc.), invested in more water efficient equipment (dish washer, washing machine), changed garden landscaping and / or invested in more efficient garden irrigation systems.

Numerous studies, which have analyzed water demand with using econometric methods, confirm that household responsiveness to price increase can be significant (see [*Arbués, et al.*, 2003; *Dalhuisen, et al.*, 2003; *Schleich and Hillenbrand*, 2009; *Worthington and Hoffman*, 2008], for reviews of existing econometric analysis of residential water demand). The methodological approach implemented in these studies consists in collecting large data sets that cover, for a few dozens of local communities socio-economic and demographic variables, economic variables (such as the average population income), housing characteristics (percentage of detached, semi-detached or collective housing, density, presence of garden) and water practice variables (such as the volume of water used). These data sets are then used as input to econometric modeling aiming at characterizing relationships between, on the one hand, water consumption variables (explained variable) and, on the other hand, the households' socio-economic characteristics, the price of water. In France, using a sample of municipalities taken in the Moselle County (Eastern France), Nauges and Thomas [*Nauges and Thomas*, 2003] confirm this short run price elasticity value (-0,26, which means that an increase of water price by 1% would result in a decrease of water demand of 0.26%). They show that the long run price elasticity can be much higher (-0.4). In Mediterranean contexts where water is scarcer and the demand higher, other authors found that long run price elasticity can be as high as –0.7 in Athens [*Ghini*, 2000] or Cyprus [*Hajispyrou, et al.*, 2002].

However, the theoretical framework underlying these econometric studies do not recognize another significant impact of the increase of water price on household behavior, which probably explains the significant long term elasticity estimated in econometric studies:

households increasingly tend to use cheap and low quality water as a substitute to expensive drinking water, for all uses which do not require high water quality (watering of gardens, toilet flushes, etc.). In France, as elsewhere in the world, households have developed different strategies depending on the local economic, climatic and environmental contexts. Some households have invested in rain water recovery system [*Australian Bureau of Statistics*, 2004; *Herrmann and Schmida*, 1999]. In rural areas, households try to obtain a pipe connection to irrigation water supply networks, in particular in Southern France [*Montginoul, et al.*, 2009] and use this alternative water resource for garden irrigation and other outdoor uses (for a similar example in the USA, see Sociology Water Lab and Colorado Institute for Irrigation Management, 2003). And others have drilled bore-holes and installed tube wells in their gardens (see for instance Meij et al. 2005 for an illustration in the Netherlands; Appleyard et al. 1999 and Australian Bureau of Statistics, 2004 for Australia, Schleich and Hillenbrand, 2009 for Germany). This paper focuses on this third strategy.

The uncontrolled development of domestic tube wells represents a significant source of environmental risk and water supply systems management problems, which are reviewed in the second section of this paper. Government agencies involved in the protection of ground water resources as well as private and public actors in charge of drinking water supply and sanitation services are becoming more and more sensitive to this problem. They recognize that a major difficulty in designing effective measures to control this phenomenon lies in the lack of understanding of households' choice behavior. This paper presents an attempt to fill this gap.

This paper is organized as follows. In the following section, we analyze the risks and management problems caused by the increase of garden boreholes, using results of a national survey conducted by the authors with 114 representatives of the decentralized administration and local governments in France. The paper then goes on with the presentation of the methodology and the case study conducted at a more local level where households and professionals installing tube wells have been interviewed (section 3). The information obtained in that case study is then used to elaborate a micro-economic behavioral model representing household decision to invest in a tube well (section 4). The behavioral model is coupled to a water demand model which estimates the aggregate impact on water demand of tube well construction at the district level, and a numerical application is carried out for a sample of 186 municipalities (section 5). The model is then used to simulate the impact of various scenarios of change in the economic and regulatory environment (section 6). In a concluding section, we discuss the policy implications of the findings.

II. RISKS RELATED TO THE DEVELOPMENT OF DOMESTIC BOREHOLES IN FRANCE

Threat or opportunity?

The increase of domestic tube wells represents either an opportunity or a threat for local communities. Certain experts consider it as an opportunity, because it reduces the total domestic demand for treated drinking water, with two positive impacts: first, it reduces pressure exerted on confined aquifers used for producing groundwater, since part of water demand (for garden irrigation notably) is satisfied with low quality, extracted from shallow aquifers by private tube wells. Second, costly investments that would be required otherwise are avoided as the total capacity of the distribution network can be kept at a minimal level. The savings made in terms of water resources and public investment are particularly significant in urban areas where most of the population lives in detached or semi-detached houses with gardens and/or swimming pools, and where outdoor uses represent a sizeable share of total water consumption. Also, because outside uses are concentrated over a short time period in summer, the development of domestic tube wells contributes to reduce the peak demand which determines the dimensions of the distribution network. An illustration of this positive impact is provided by the case of the city of Perth in Western Australia [*Appleyard, et* *al.*, 1999; *Saayman and Adams*, 2002]. In this city, the number of private tube wells is estimated at 150 000 (one house every four has drilled, a figure confirmed by the Australian Bureau of Statistics, 2004), resulting in a yearly reduction of the total drinking water demand of 184 millions cubic meters. In some extreme cases, experts would go as far as recommending that public authorities encourage (through subsidies for instance) the development of private tube wells (see for instance [*Saayman and Adams*, 2002], for the case of Cape Town, South Africa). This, however, ignores the multiple environmental threats, health risks and public utilities management problems caused by the uncontrolled increase of domestic tube wells.

From an environmental point of view, the development of domestic tube wells generates three major risks. First, it may cause an overexploitation of shallow aquifers, leading to a drop in water tables, land subsidence and, in coastal areas, to sea water intrusion which causes an irreversible environmental damage. Such cases of sea water intrusion due to “drilling and pumping fever” are for instance reported by [*Aguilera-Klink, et al.*, 2000] in Tenerife island and by [*Kent, et al.*, 2002] in Mallorca. In urban areas, the problem of over-exploitation of shallow aquifers by private tube wells is exacerbated by the fact that urbanization leads to an increase of impervious surfaces (paved roads, parking lots, roofs) which prevents rainwater from infiltrating into the ground [*Carmon, et al.*, 1997].

Moreover, private tube wells represent a significant risk of pollution for high quality confined aquifers exploited for drinking water production. According to public authorities, domestic tube wells are not always constructed according to standards [*Miquel and Revol*, 2003]: to reduce tube well prices (approximately by half), some drilling companies do not install the cemented casing that should be present to isolate the tube well from the poor quality shallow aquifer layers it crosses. To reduce that risk, the French professional Union of Drilling Companies edited in 1998 a “Drilling Charter” which specifies the minimum technical requirements that must be followed by drilling companies when constructing a borehole. Only 60 of the 600 drilling companies have however signed that Charter. As a result, tube wells often join up previously distinct hydrogeological layers at hundreds – if not thousands- points, thus allowing good quality aquifer layers to become contaminated by polluted shallow aquifers (mainly contamination with nitrates and pesticides). Third, and for the same reason, they may be responsible for accidental point source pollution of deep aquifers by surface pollutants (fertilizers and pesticides used for gardening, hydrocarbons and solvents running off from water drainage sources, etc.).

A second type of risk is related to public health. For economic reasons, households may be tempted to substitute cheap untreated groundwater to expensive drinking water for indoor uses, such as toilet flushing, washing machine but also showers and sometimes cooking. Technically, this simply requires that a dual pipe network be installed in the house. The regular inhalation (showers) or consumption (drinking, cooking) of water may be hazardous as aquifer tapped by households may be affected by the most common forms of diffuse and point source pollution (nitrates and pesticides; chlorinated solvent, polycyclic aromatic hydrocarbons, etc.). Also, the construction of dual systems that enable indoor uses of untreated groundwater generates a risk of contamination of the municipal drinking water network by poor quality groundwater. This risk is due to the fact that, in most houses equipped with a dual system, the drinking water and the untreated water pluming systems are not totally separate but interconnected (despite this being formally prohibited by law, in France for instance). A wrong manipulation of the gate that separates the two pluming systems results in backflow of water pumped in the tube well (high pressure) towards the public network (low pressure). Such incidents are frequently reported and they represent a major concern for public and private drinking water utilities.

From a management point of view, municipalities and water utilities are increasingly concerned by the development of private tube wells which may actually generate more management problems than they solve. In particular, this development, which results from individual choices, is relatively difficult to anticipate. As a consequence, it is extremely hard for district authorities and water utilities to predict future demands for drinking water and to plan network development accordingly. Because they did not anticipate the development of hundreds of tube wells by households, certain district authorities have over estimated the drinking water demand and constructed over dimensioned infrastructures [*Meij, et al.*, 2005]. To balance their budget, they were compelled to implement sharp increase of water price, which in turn has provided incentives for households to drill boreholes. Another source of uncertainty is also reported: during periods of drought (such as summer 2003 in France), hundreds of domestic tube wells tapping shallow aquifers may run dry. The concerned households then compensate the temporary failure of their own water supply system though a significant increase in drinking water use. This results in a drastic increase in total drinking water demand that public utilities may not be able to satisfy – unless they had decided to over-dimension their network to be able to face such crisis.

Finally, the indoor use of untreated groundwater (for toilet flushes, washing machines, etc.) creates financial difficulties for the actors operating wastewater treatment plants, who generally charge users accordingly to the drinking water volume they consume. Households having a private tube well consume very little drinking water, thus pay very little sanitation charges although they discharge a significant volume of wastewater. When the proportion of households using a tube well increases, the cost recovery ratio (for the sewage service) deteriorates which forces the manager to raise water and sewage charges. This induces inequity as the bulk of the total sewage cost is paid by households who do not have their own water supply.

Significance of the phenomenon in France: results of a national survey

In order to assess the extent of the problem described above, we undertook a national survey. A semi-structured questionnaire was designed and sent by mail to selected public experts involved in urban water management in each of the 96 metropolitan French counties ("départements" in French). Experts consulted were taken within: (i) the Government Department for Social, Heath and Sanitation Affairs (DDASS) in charge of implementing laws and regulation related to drinking water; (ii) the Government Department for Agriculture and Rural Affairs, in charge of supporting small and medium municipalities with regards to issues related to investment in the water and sanitation sector; (iii) County Councils ("Conseils Généraux") which administer the National solidarity Funds for Water Supply Development (FNDAE) at the county level and (iv) County level associations of mayors, likely to be informed of the difficulties faced at the municipal level for all water related issues (drinking water supply being the mayor's responsibility in France). Each consulted expert was asked to give his views on: the level and the evolution (past and future) of private tube wells development in the county; the opportunities and problems caused; and the strategies implemented by various public actors to control the development of individual water supply systems. The questionnaire also included questions on the development of other alternative water supply systems such as rain water recovery systems and connection to collective irrigation water distribution networks. The related results are not discussed in this article.

A total of 114 complete questionnaires were returned, covering 78 metropolitan counties. Most of the information was provided by decentralized Government Departments (Agriculture and Rural Development Affairs and Health and Social Affairs) which represent the 70% of the returned questionnaires, against 26% for County Councils and 4% for Mayor Associations. The key results of the survey are the following (see figure 1): the presence of domestic tube wells (or wells) is reported in 85% of the 78 counties covered by the survey.

Against our expectation, there is no clear relationship between the reported presence of tube wells and the geographic and climatic characteristics of the counties: the presence of tube wells is not limited to the South part of France, where water needs in summer are really high and many tube wells are also reported in North of France.

Experts generally agree that domestic boreholes represent a threat (90% of the respondents) although some of them (20%) acknowledge that the risks described in the previous sections are partly counter-balanced positive impacts. The major concerns quoted by the experts are: the risk of back-flow of untreated water in the public network (70%); the financial difficulties caused to Water Utilities because of the reduction of total water sales after the investments have been made (44%); the financial loss due to the fact that tube well owners do not pay for the treatment of the waste water they discharge in the sewerage system (39%); the public health risk due to the consumption by households of water which does not comply with the drinking water standards (23%); and the environmental risk of groundwater pollution and/or over-exploitation (5%). The fact that this issue hardly quoted is explained by the fact that environmental protection is not the primary concern of the consulted experts (staff from the Environment Protection Departments were not included in the sample). Interestingly, none of the experts reported cases where the development of domestic tube wells would have been encouraged by public actors at the municipal or the county level. However, few cases where municipalities encourage the construction of rainwater recovery systems have been quoted. One of the objectives of this policy, implemented at the municipal level, is to reduce the total volume of rain water that goes in the sewage system and to the waste water treatment plant. On the contrary, experts systematically report that drinking water utilities are trying to develop strategies aiming at keeping the “drilling fever” under control. Theses strategies are described in the following section.

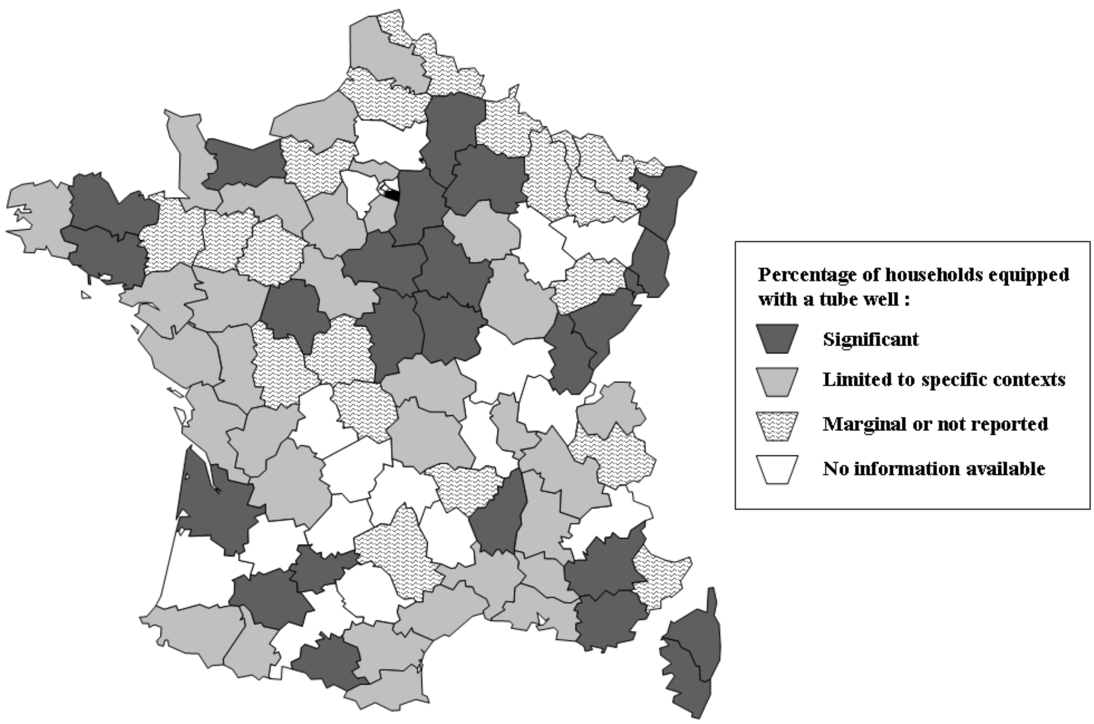


Figure 1: French counties where the presence of domestic tube wells is reported.

Inadequate regulation

A large majority of the experts consulted (61% of the respondents mentioning the existence of private wells, representing 41 counties) consider that the public actors –at the municipal or county level – do not initiate any specific law enforcement action to control the development of private tube wells. This is due to the fact that drilling of private boreholes is not an activity covered by a specific piece of legislation. Instead, this issue lies at the intersection of the civil code, the mining code, the environment protection code, and the code of Municipalities.

Drilling activity is absolutely not regulated in France: contractors can drill without obtaining a specific license and boreholes can be made without asking for a permit. The only constraint imposed by the Mining Code (article 131) is the obligation for the tube well owner to submit to the Government Department for Mining and Industry and to the French Geological Survey (BRGM) a drilling report specifying the location of all boreholes deeper than ten meters together with the log. Although this provision applies to domestic boreholes, the declarations are rarely (if not never) made. Similarly, water abstraction by households is not really constrained. According to article 641 of the Civil Code, everybody has the right to "*freely use underground and spring water on their land, provided that it is not running surface water*", and therefore to build a well or tube well. The decree of 20/12/2001 on water used for human consumption (which transposes the Directive 98/83/EC relating to the quality of water intended for human consumption) states that "*no authorization shall be necessary for the extraction of water from the natural environment for personal use by a family*". Some additional constraints are however imposed when water volumes abstracted exceed the needs of a family. The decree number 205 dated 06/03/ implementing the French Water Law of January 3rd 1992 imposes that any water abstraction exceeding 8 m^3/hour be declared to the administration in charge of water management. For abstraction exceeding 80 m^3/hour, an official water abstraction permit must be obtained. The decree also specifies that pumping for domestic use, that is, less than 1000 m^3/year (that is almost all households), is exempt from the above-mentioned procedure. The lonely constraint put by the decree of 20/12/2001 is that every well or tube well must have a meter, to control if a household extract more or less that 1000 m^3/year. Moreover, article R.372-10 of the Code of Municipalities specifies that any person whose house is connected to a collective sewage system and who is supplied, totally or partially, by a water source other than the mains supply should declare this to the Municipal Council. Finally, it is officially forbidden (except with permission from the prefect) to connect a private well to the interior water supply to avoid problems of backflow (decree of 20/12/01 quoted above).

To compensate the inadequacy of the legislation, public authorities have however developed specific strategies to control the development of private tube well where they represent a threat for the environment or for the performance of public water utilities. A smaller group of experts consulted (9% of the respondents, representing 6 counties) report that communication campaigns have been undertaken by water utilities in order to make citizen sensitive to the legal constraints related to boreholes and to raise awareness on citizen's liability in case of problem (backflow in the mains supply or environmental pollution). Other experts (17% of the respondents, 14 counties) also report that certain water utilities offer to install a separate tap and water meter in the gardens of houses and to charge a reduced water rate (excluding the sanitation charge) for the water used outdoors (irrigation of gardens, filling of swimming pools). The objective of this pricing policy (referred to as "green-pricing") is to reduce the attractiveness of private tube wells, which are mainly used (in volume) for watering gardens. Another similar (but less frequent) strategy adopted by certain municipalities consists in charging a flat rate fee for waste water treatment service. The amount of flat rate is often indexed on the number of household members. This pricing strategy also contributes to reduce the profitability of garden tube wells. Using these two economic instruments together (green pricing and sewerage flat rate fee) can have a "pull and push" effect, the green pricing being used as a carrot whereas the flat rate sanitation fee is used as a stick.

To deeper understand the determinants of households' behavior toward tube wells, to simulate the future evolution and to evaluate the impact of different instruments that can be put to fight against this development, it was important to go deeper in a more local case.

III. METHODOLOGY AND CASE STUDY

Background: possible modeling approaches

A local case study was conducted in view of assessing empirically how the attractiveness of tube well could be influenced by various economic and regulatory instruments. The objectives were: (i) to identify the factors determining households drilling decision; (ii) to assess to what extent this decision is motivated by financial concerns; (iii) to develop a choice behavior model and ; (iv) using this model, to assess the potential impact of various regulatory and economic instruments on households choice behavior.

The approach developed assumes that households invest in the construction of a tube well if this strategy offers the highest level of utility (discrete choice theory). Modeling household behavior consists in assessing the utility associated to each strategy (supply with tube well or tap water only). Two distinct modeling approaches were envisaged:

The first one consists in developing and assessing a statistical model using multivariate regression logit (or probit) model where the dependent variable is the probability that households drills a borehole. This probability is expressed as a function of drinking water price, groundwater accessibility, composition and socio-economic characteristics of the family, and house characteristics (size, garden swimming pool, etc). Similar approaches (using a multinomial logit model) have been implemented in contexts where households can choose between several water supply sources [*Mu, et al.*, 1990]. It has also been used to analyze discrete choice experiments (stated preferences and not revealed preferences as in our case) where households are offered to chose between alternative hypothetical water supply scenarios characterized by different service quality levels [*Haider and Rasid*, 2002; *Whittington, et al.*, 2002]. This approach, however, supposes an access to (or the constitution of) a large database on several hundreds of households. This proved to be a major constraint in the French case as existing census of boreholes are totally unreliable. If boreholes made by water companies and industries are generally registered, very few households declare the tube wells or wells which they construct, contrary to their legal obligations to do so. This statement is based on the direct experience of one of the authors who is currently working for the French institution in charge of maintaining a national database on boreholes and underground works. No data therefore exist that could serve as a basis for constituting a sample of households to be interviewed and then implement an econometric analysis of households behavior.

The second approach, which we adopted, consists in developing a mathematical micro-economic model which computes the utility associated to each strategy for different types of households. This approach is based on the assumption that each household decides to install an individual tube well if this strategy provides a higher level of utility than the utility of the "drinking water supply only" strategy. A simple version of that sort of model would assess the cost and the benefits of drilling (i.e. savings on the drinking water bill, increased pressure of water supply, higher reliability of the service, etc), and it would predict that a tube well be constructed by a household if the benefits exceed the cost of drilling. Costs and benefits obviously depend on households' characteristics (composition and socio-economic characteristics of the family, characteristics of the house…), policy variables (level and price of drinking water price for instance) and environmental variables (depth of groundwater, climate which determines garden water requirements, etc). The model can then be used to simulate the impact of a change in policy input parameters on decision-making of various types of household.

Characteristics of the case study area

The modeling work presented bellow is based on several years of field work conducted in a coastal area of Languedoc Roussillon region. The case study covers an area of about 5000 km². It encompasses 310 municipalities depending from the three major water resources of this area: the Orb and Hérault rivers; the alluvial aquifers of these two rivers; and the Astien sand confined aquifer (see figure 2). This zone is characterized by high rapid demographic growth (1.6% per year on average) mainly due to migration from the North of France and other European regions. Migrants generally settle in detached or semi-detached houses, almost always with gardens and very often a swimming pool. Faced with increasing water demands generated by this demographic influx, municipalities (which sets the water price and, in the Hérault region, generally operates drinking water supply and sanitation services) have made significant investments in the drinking water sector (new groundwater extraction works, new tanks, extension of the distribution network, etc.). The resulting water price increase and the fear that this trend would continue has incited many households to build their own garden tube well, in particular where underground water is relatively easily accessible in the area.

The fieldwork was carried out in three steps. We first carried out interviews: with companies drilling boreholes and installing equipment (like pumps and garden irrigation systems), and with plumbers installing water mains and dual water systems all working within the study zone. Fifteen detailed interviews were carried face-to-face at the respondents' office, as informally as possible, using semi-directive interviewing guidelines. The second step consisted in a detailed analysis of a municipality of 2000 inhabitants (Canet d'Hérault), situated thirty kilometers from Montpellier, where we interviewed 55 households. The objective of this case study was to investigate in detail how households decide to drill and how they use their tube well. The information collected through interviews was cross checked with an analysis of water consumption of more than 800 individual households', leading to the identification of all households owning a private borehole. The third step of the field work consisted in collecting information related to water price, geology and urban characteristics for all 310 municipalities of the study area.

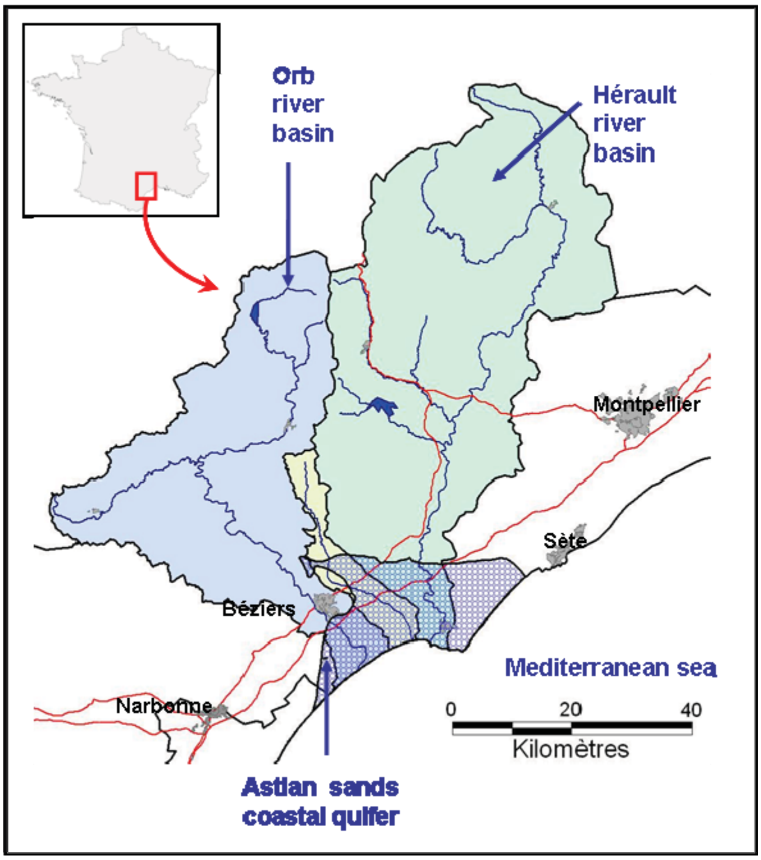


Figure 2: Location of the case study area.

Analyzing households' decision to drill

According to professionals (drilling companies, plumbers, etc.), between 10 and 15% of households living in the study zone have installed a garden tube well. This proportion is particularly high in alluvial zones where the water table is close by (up to 50% of households do drill) as well as in municipalities where water prices are high. In the municipality of Canet, we found a proportion of 7% of households by crossing information from various sources. The majority of professionals we met confirmed that the rate at which these tube wells were being installed had increased in recent years, due to water price increase and the rapid population expansion currently taking place in the area.

Interviews with households and professionals also suggest that the main reason motivating people to drill a tube well is to make savings on the water bill. Interviews conducted in the

Hérault valley reveal that, before deciding to drill, households make a basic assessment of the profitability of their investment by comparing the expected cost of drilling with the expected savings on the water bill. The parameters taken into account are the average water consumption (volume per year), the price of drinking water and sanitation (charged together on the basis of drinking water use); the construction cost of the tube well; and the recurrent cost of pumping. Most of the households over-estimate the service life of the tube well, underestimate the pumping energy and maintenance costs and do not use any discount rate in their calculations. They generally base their calculation on the assumption that groundwater will only be used outdoors (for garden watering, car washing, swimming pool filling, etc) and that they will continue using drinking water indoors (kitchen, showers, toilets, etc). Some of them however plan to install a dual network indoors in order to use untreated (cheap) groundwater for toilet flushing, washing machine and possibly showers and to reduce drinking water consumption to a minimum. Households are apparently aware of the uncertainty related to the depth at which groundwater can be found, their perception of the level of uncertainty being based on direct observation (depth at which neighbors have drilled a well) and information provided by the drilling company or the Regional office of the National Geological Survey (Brgm). Finally, some households take into account possible future trends of drinking water price (upwards trend expected to continue) to make their calculation.

Structure of the economic model

This information collected through interviews was used to develop a choice model simulating households' behavior and the impact of individual decisions on total water demand at the district level. The model developed is composed of two modules operating at district level (Figure 3): the first module is a behavioral micro-economic model representing households' decision to invest (or not) in a tube well; for a given physical and economic environment (groundwater accessibility, water prices), it assesses the minimum water consumption (Q_{min}) above which the construction of a tube well is a profitable investment. The second module takes this threshold water consumption value as an input, and it estimates the percentage of households likely to drill and the total volume of urban water saved thanks to the access to groundwater. These two modules are connected to a database describing the hydrogeological, economic and demographic characteristics of a sample of municipalities. A scenario generator is then connected to the model, enabling to assess the impact of various water management scenarios. The following sections present the model with more details.

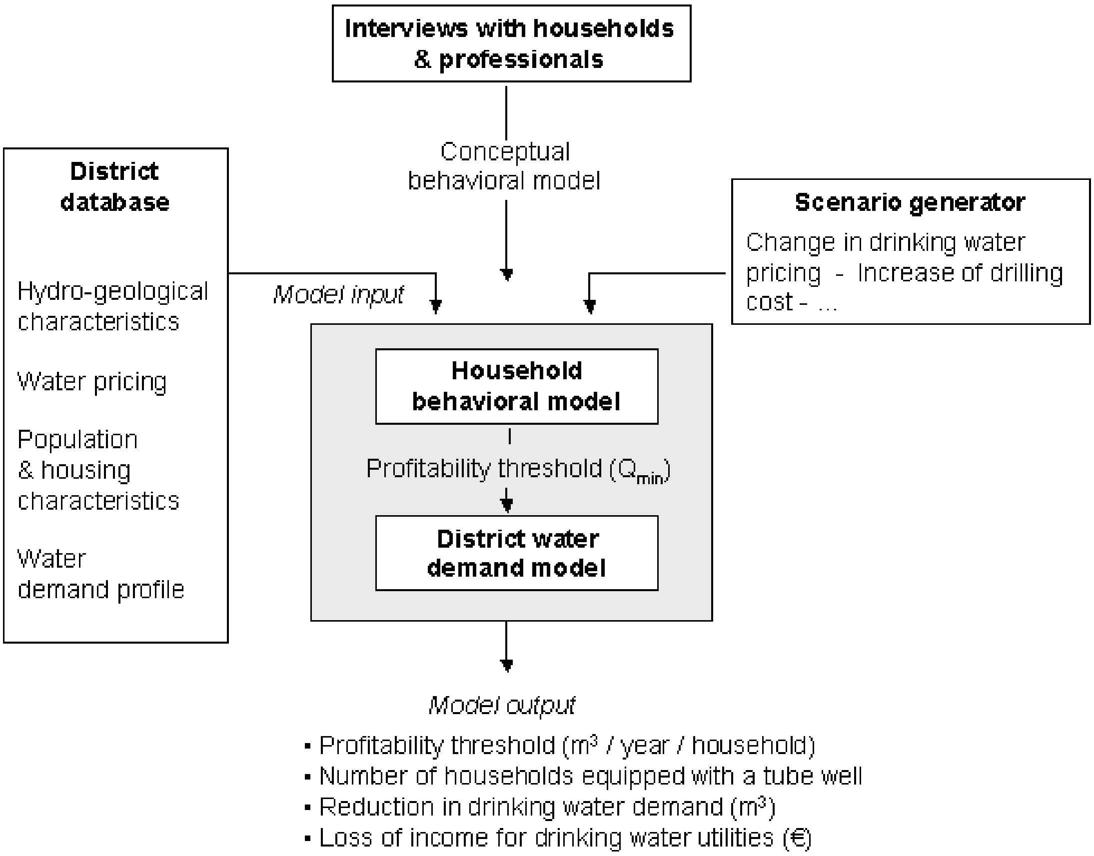


Figure 3: Structure of the economic model

IV. MODELING HOUSEHOLD BEHAVIOR

Conceptual model

Households are assumed to construct a tube well if the total annual cost of groundwater exploitation (capital and recurring costs) is lower than savings they expect to make on their water bill. The total annual cost (C_{annual}) of tube well exploitation and the expected annual savings (S_{annual}) write as follows:

$$C_{annual} = cH \times \frac{a\,(1+a)^{T}}{(1+a)^{T}-1} + p_g Q \qquad (1)$$

and

$$S_{annual} = Q.p_d \qquad (2)$$

where:

H is the depth at which groundwater can be obtained (unit meters); H determines the investment and the pumping costs;

T is the expected lifetime of the tube well and pumping equipment (unit year);

a is the discount rate;

c is the drilling cost (unit €/meter) which depends on the type of aquifer;

Q is the volume of water for which a substitution is possible (unit m^3/year);

p_d is the marginal price of water from public supply (including wastewater treatment charges and taxes, in(€/m^3);

p_g is the cost of groundwater pumping (€/m^3).

The construction of a tube well is a profitable investment when the volume of water for which a substitution is possible is equal to (or greater than) a threshold value, noted Q_{min} which is such as the expected savings S is equal to the expected cost C, that is:

$$Q_{\min} = \frac{c.H}{(p_d - p_g)} \times \frac{a\,(1+a)^T}{(1+a)^T - 1} \qquad (3)$$

We further assume that households equipped with a tube-well will continue to use potable public water supply for cooking and taking showers (estimated at 50 m^3 per year). Households investing in a borehole are therefore those who are currently consuming Q_{min}+50. This minimum consumption is noted C_{min} hereafter.

Taking uncertainty into account

Given the uncertainty surrounding the depth at which water will be reached, and the risk of failure (dry-drilling), the investment cost (C) and the amount of savings made on bills (S) are uncertain deciding elements. Two sources of uncertainty should be distinguished. The first is linked to the risk of not finding water in the aquifer layer aimed for. This risk depends on the geology: the likelihood of success (noted Л) is thus weaker on Jurassic limestone plateau (0.2 to 0.3) than in the Miocene formations of the Hérault plain terraces (0.4 to 0.6) or than in the quaternary alluvial deposits of the Hérault valley (0.8 to 0.95). Information gathered by the survey clearly outlined that the households are aware of this risk, and that they consider it when making their decision, by anticipating drilling down to the second aquifer layer in case of failure to find water in the first one.

The second source of uncertainty is linked with the variability of depth *H* at which water can be found in any particular aquifer layer aimed for. This variability is higher in fractured or strongly heterogeneous aquifer layers (limestone, marl and complex alluvial deposits) but is much lower in more homogenous environments like sands (sand layers of Astien on the coastline) or quaternary alluvial deposits. As interviews suggest, households are aware of this uncertainty: when assessing the financial profitability of a borehole project, they base their calculations on subjective depth hypotheses. This subjective hypothesis, which we will call "depth expectancy" here, varied from one individual to another depending on their perception of the risk. Thus, a household whose income is small is assumed to have a bigger aversion to risking such an undertaking than a household whose bigger financial resources would mean that a failure would not have serious consequences for them. Depth expectancy ($\widetilde{H}$) is assumed to be equal to the average depth ($\overline{H}$) at which water can be found (value based on objective data) increased by a subjective depth (the risk premium) equal to standard deviation (σ) multiplied by the risk aversion coefficient (Φ). This approach is inspired from behavioral models developed by [*Freund*, 1956] which depicts farmers' cropping pattern decision in situations of market or resource uncertainty and [*Markowitz*, 1952] representing decisions of agents in uncertain financial market. In the present case, Φ calibrated using the observations made in the Canet municipality, which is the only location where we have an accurate estimate of the number of boreholes.

$$\widetilde{H} = \overline{H} - \Phi\sigma \qquad (4)$$

These two sources of uncertainty impact the expected investment cost. If the first aquifer layer A_1 is productive (probability $Л_1$), the cost is equal to the depth at which water is expected to be found at $\widetilde{H}_1$ multiplied by the cost per linear meter of borehole drilling and well casing. If the first layer is unproductive (probability 1-$Л_1$), borehole must be drilled further to reach the second aquifer layer at $\widetilde{H}_2$. Assuming that this second layer is productive (probability $Л_1.Л_2$), the cost is equal to the depth reached multiplied by the cost per linear meter of borehole drilling and well casing. Otherwise, if the hole is dry-drilled (probability equal to [1-$Л_1$].[1-$Л_2$]), the cost is equal to the depth reached multiplied only by the cost per linear meter of borehole drilling (the well does not need casing in this case). In this worst-case scenario, the amount spent represents a dead loss for the household who must continue to be supplied with urban water.

Then, the annual expected cost (noted $\widetilde{C}_{annual}$) is defined as the sum of the cost of each event described above multiplied by the probability of its occurrence, which writes as follows:

$$\widetilde{C}_{annual} = a \times \frac{(1+a)^T}{(1+a)^T - 1} \times [\pi_1.c_1(H_1 + \Phi\sigma_1) + (1-\pi_1)\pi_2.c_2(H_2 + \Phi\sigma_2) + + (1-\pi_1)(1-\pi_2).\frac{c_2}{2}(H_2 + \Phi\sigma_2)]$$
$$+ Q\,[\pi_1\, p_g + (1-\pi_1)\pi_2\, p_g + (1-\pi_1)(1-\pi_2)\, p_d] \qquad (5)$$

Where :

a is the discount rate;

H_1 and H_2 are the average depth of water in the first and second aquifers;

c_1 and c_2 are the drilling cost per meter for the first and second aquifers;

Φ is the households risk aversion coefficient;

p_d is the price charged per cubic meter for drinking water supply and sanitation services;

p_g : pumping cost in the tube well per cubic meter extracted;

Q : quantity of water for which a resource substitution is possible (outdoor uses, eventually toilet uses and washing machine).

Using these notations, and after simplification, the minimum yearly volume of water to be pumped (profitability threshold, noted Q_{min}) writes as follows:

$$Q_{\min} = \frac{\pi_1\, c_1\left(\overline{H}_1 + \Phi\sigma_1\right) - \frac{c_2}{2}\left(\overline{H}_2 + \Phi\sigma_2\right)\left(\pi_1 - \pi_2 + \pi_1\,\pi_2 - 1\right)}{\left(p_d - p_g\right)\left(\pi_1 + \pi_2 - \pi_1\,\pi_2\right)} \times \frac{a\,(1+a)^T}{(1+a)^T - 1} \qquad (6)$$

This threshold value Q_{min} is a function of parameters which are supposed to be uniform across households at the district level. Its actual value was then calculated for a sample of municipalities for which the required information has been collected.

Numerical application of the model at regional level

The economic model is then applied to a sample of 186 municipalities (out of 310) where water pricing structures and levels are known and where it is possible to find groundwater. We calculate for each municipality the threshold value Q_{min}. These municipalities are representative of the diversity of geological context (Jurassic limestone sub-soil, alluvial deposits, Astien sands, Miocene marl) and of price levels in the region. Urban water price data were collected through a large mail survey. A detailed analysis of the geological map and borehole data available at the French Geological Survey (Brgm) is then conducted to identify the nature of the first two aquifer layers in each district (average depths, standard deviations, and the risk of a dry-drilling). Demographic and housing data are taken from the most recent population census carried out in 2006 by the National Institute for Statistics and Economic Studies (INSEE). Information collected is related to number of households, type of occupancy (permanent or temporary) and type of housing (detached houses or collective building, with or without garden).

Results show that borehole drilling's profitability varies widely in the sample. This volume is lower than 70 m^3 in only one municipality where it represents a profitable investment for almost any owner of detached house. The threshold ranges between 120 m^3 and 250 m^3 for another 17% of the municipalities where boreholes may attract owners of detached houses with small to medium size irrigated gardens with a swimming pool. In 21% of municipalities, the threshold ranges between 250 and 500 m^3 meaning that only owners of houses with large and intensively irrigated gardens are likely to drill a borehole. Above 500 m^3, drilling a borehole is not a profitable investment and no household is expected to drill (62% of the municipalities).

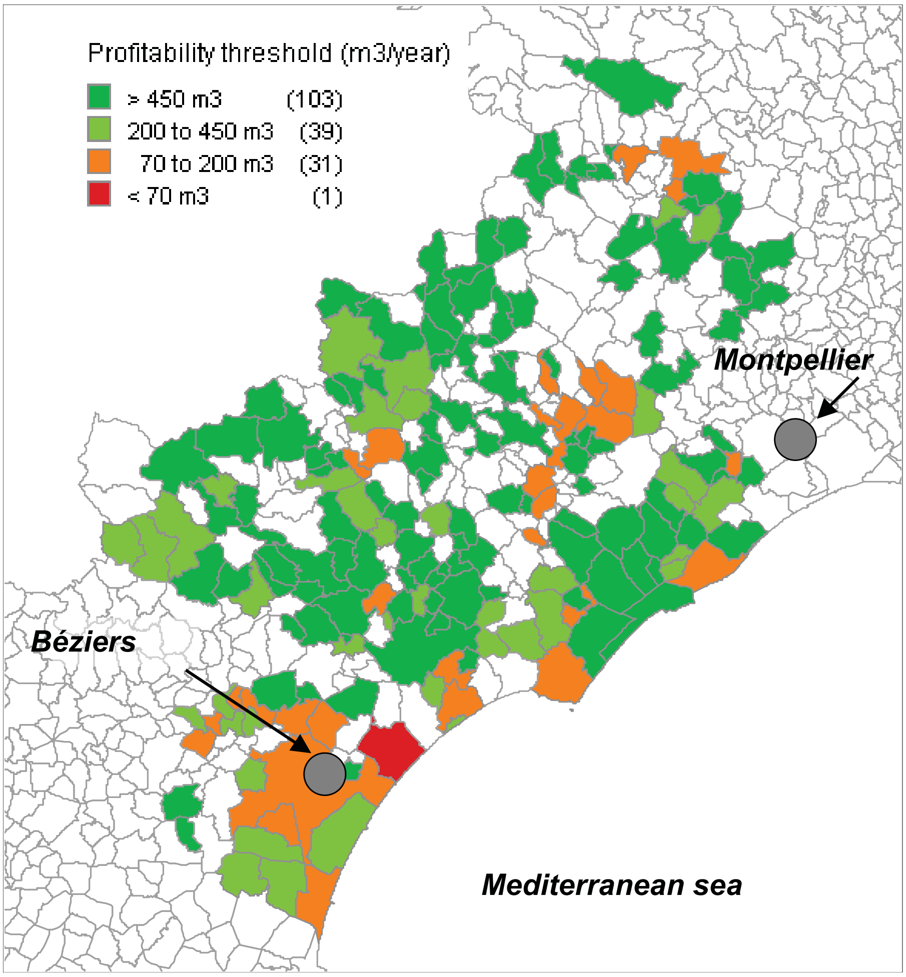


Figure 4: Estimated profitability threshold value in the 2006 reference situation (in m^3 /year/household).

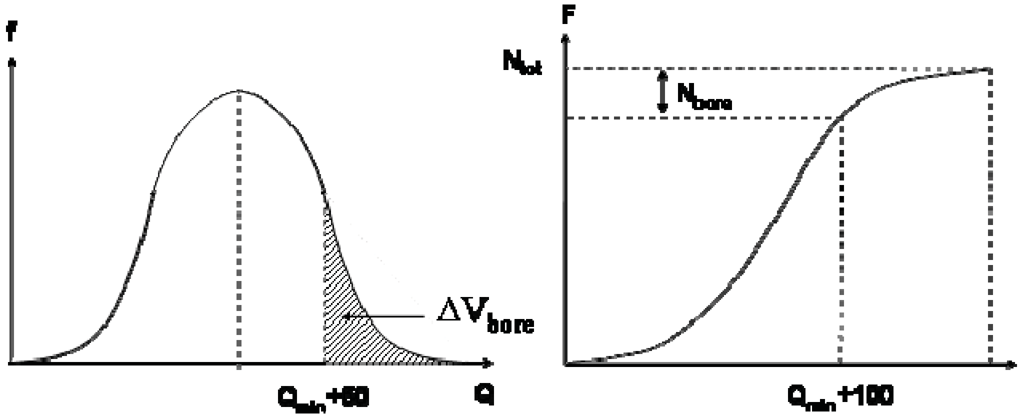
V. MODELING THE IMPACT OF TUBE WELL DEVELOPMENT ON DISTRICT WATER DEMAND

A second module was then developed to assess the cumulative impact of households' decision on total water demand at district level. This model takes as input (i) demographic and housing characteristics of each district, (ii) a water demand profile, and (iii) the tube well profitability threshold (Q_{min}) estimated with the behavioral model. As outputs, it assesses the number of households likely to drill a borehole in the district and estimates the corresponding volume of raw water likely to be pumped at least (if no change in water consumption behavior) in the aquifer – and the related decrease in urban water demand. The combined model can then be used to simulate the impact of various scenarios (including changes in urban water pricing level and structure) on total drinking water demand.

The water demand modeling principle is the following. For a given district where the tube well profitability threshold (noted Q_{min}) has been estimated with the behavioral model, the Water Demand Model assesses the number of households N_{bore} likely to drill a borehole and the corresponding reduction in urban water demand. The estimation relies on the assumption that households will drill a borehole if their yearly current water consumption for outdoor uses (garden watering, swimming pool) is higher than Q_{min}. We further assume that households equipped with a borehole will continue using a minimum of 50 m^3 per year of drinking water for cooking, drinking, showers, etc. This implies that only households consuming more that (Q_{min} + 50) m^3/year will invest in a tubewell.

The number of households N_{bore} is estimated using the district water demand profile, defined as the distribution of households per classes of water consumption (**figure 5**). The current water consumption of the N_{bore} households, noted ΔV_{bore}, is also estimated from the water demand profile (ΔV is graphically represented by the shaded area on the right hand side of the distribution).

To assess the reduction in urban water demand, we further assume that only 80% of the concerned households will effectively drill a borehole (the remaining 20% do not invest either because they face cash flow constraints, or because the access of the drilling machine to the garden is not possible or would generate too much damage to the vegetation in case of landscaped gardens. The model estimates the reduction in urban water demand due to the presence of boreholes. It also estimates the loss of income for the urban water utility, taking into account water and sewerage services pricing information.



Q is the total volume of water consumed per household in m^3.
f is the frequency of urban water consumption.
F is the cumulative frequency of urban water consumption.
$\mathbf{N_{bore}}$ is the number of households for whom drilling a borehole is a profitable option.
$\mathbf{N_{tot}}$ is the number of households living in the municipality.
$\mathbf{\Delta V_{bore}}$ (area shaded in grey) is the current urban water consumption of households for whom drilling a borehole is a profitable option.

Figure 5: Distribution of households per class of water consumption (water demand profile).

A typical water demand profile, defined as the standard distribution of households per classes of water consumption is constructed using water bill data (892 customers, of which 372 detached houses) collected in Canet. Assuming that this municipality is representative of the region, this water demand profile is then adjusted to each of the 186 municipalities, using demographic and housing data.

Results

The total number of boreholes is estimated at 7200 in the entire case study area. Their density differs significantly from one municipality to another. The model predicts that no – or very few - boreholes should have been drilled in 108 municipalities. At the other extreme, borehole density is relatively high in 18 municipalities where 25 to 50% of detached houses' owners are likely to have drilled. The situation is worse in 7 municipalities more than 50% of detached houses owners are expected to own a borehole.

Table 1: Distribution of proportion of households having drilled a borehole.

Proportion of households equipped with a borehole in municipalities	0%	0 to 1%	1 to 10%	10-25%	25-50%	>50%
Number of municipalities in that class	60	48	28	25	18	7
Average threshold value (in m^3 /year/household)	2250	638	392	248	144	82

Sensitivity test

One of the major caveat of the modeling approach presented above lies in the difficulty to calibrate and validate the model. Since no reliable boreholes census exist, predicted valued can't be confronted to observed values. The calibration of parameters such as risk aversion of discount rate considered by households is therefore not possible, except for one municipality (Canet) were the number of boreholes is known. A sensitivity analysis was therefore conducted to assess the robustness of the model.

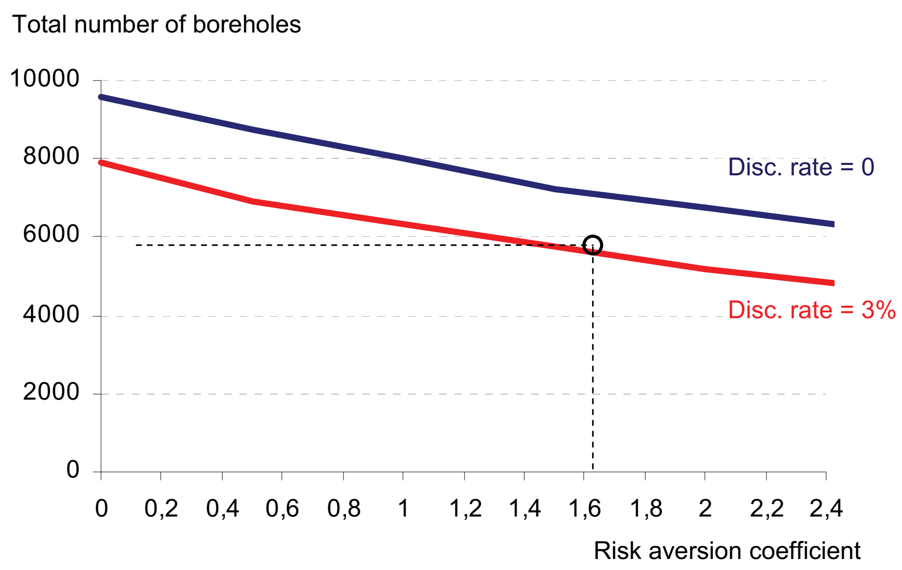


Figure 6: Sensitivity of the model to risk aversion coefficient and discount rate.

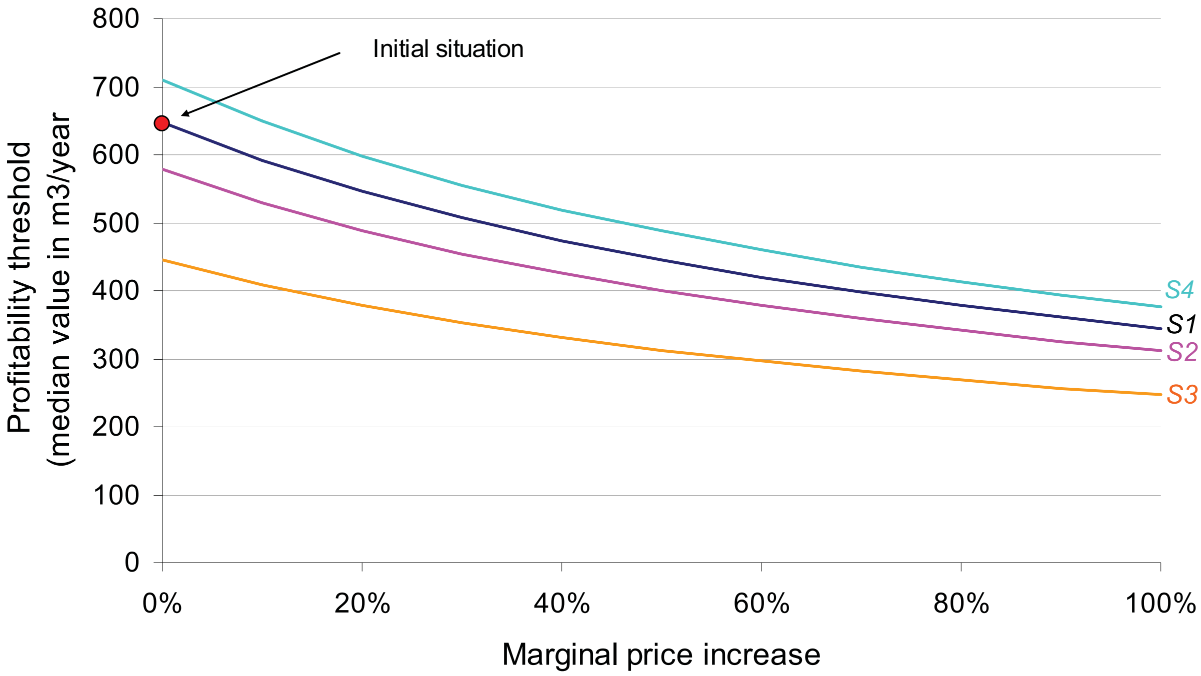
VI. SIMULATING THE IMPACT OF POLICY SCENARIOS

Expected evolution: towards an aggravation of the phenomenon

The economic model is then used to characterize the impact of economic changes expected to occur in the near future (trend scenario) as well as the impact of possible regulatory or economic instruments which could be implemented to reduce the attractiveness of drilling. Three drivers are likely to reinforce economic incentives for households to drill private wells.

First, Drinking Water Utilities will be compelled to change their tariff structure to comply with the requirements of the 2006 French Water law. This law says that, after January 2010, the fixed part of the water bill shall not exceed 30% of the total water bill (calculated for a consumption of 120m^3 /year). This change in water pricing structure, for which Consumer Associations have been militating actively (they wanted to totally suppress the fixed part), will automatically lead to an increase of volumetric water price (water utilities have to balance their budget). Officials from Drinking Water Utilities were concerned that this would encourage households to drill. Using our model, we show that this will not be the case in the studied area, the limitation of the fixed part of the bill leading to an increase of 1% of the total number of boreholes. A complete suppression of the fixed part would lead to an increase of 20% of the total number of boreholes.

The second driver is the expected increase in water price level which is likely to occur in France as in other European countries [*OECD*, 1999]. This trend is due to investments which still have to be made to meet the objectives of new European regulations French water utilities will have to undertake significant investments, estimated at 27 billion €, to modernize wastewater treatment plants and sewage systems in order to meet the objectives of the Urban Wastewater Directive by the year 2013. Significant investment (estimated at 5 billion €) will also be needed to replace lead pipes in the public distribution system [*Hrovatin and Bailey*, 2001]. Moreover, water district must soon renew their water distribution network, in particular in small municipalities such as those studied here, where no preventive renewal has been carried out for decades. In the South-eastern French river basin administrative district, the cost of network renewal is estimated at 10 billion € for the next twenty year [*Agence de l'Eau Rhône-Méditerranée-Corse*, 2002]. In addition, the cost of water resource protection and restoration measures imposed by the European Water Framework Directive will probably lead to an increase of abstraction charges to cover the extra administrative and monitoring costs [*Kallis and Butler*, 2001]. We simulated the impact of various price increase levels on the profitability threshold. Figure 7 shows that, if marginal price doubles, profitability threshold decreases from 650 to 350 m^3 and the total number of boreholes increases by 86 %.



S1 = price increase only. S2 = change in pricing structure (fixed part reduced) and price level increase. S3 = S2 + 25% decrease in drilling costs. S4 = S2 + 25% increase in drilling cost.

Figure 7: Evolution of profitability threshold (in 3/year/household) with price increase, with different scenarios.

The third driver is drilling cost. If the number of drilling firms on the market continues to rise, increasing competition could result in a decrease of drilling cost (but also to the reduction of borehole casing and cementing quality, most of the boreholes not complying with the quality standards). Relying on expert advice, we assume that borehole drilling costs could be reduced of 25% if the French Government does not reinforce the control of private well construction quality. Figure 7 shows the evolution of profitability threshold when drilling costs decrease.

Regulating the drilling fever through regulation

Increasing drilling cost is one way to control the development of boreholes. This can be achieved by imposing new regulations on drilling activities (implying a modification of the exiting legislation) in view of ruling out of business contractors not following bore well construction standards. This would not only reduce the negative environmental impacts described in the first part of the paper but also lead to an increase of drilling market prices, thus reducing economic incentives for households to drill. The effect of increasing drilling cost on borehole profitability is depicted on figure 7.

From an operation point of view, drilling companies could to be licensed by the state, as this is the case Portugal, Australia, New Zealand, USA, and Canada where contractors have to pass an exam certifying that they have the minimum required knowledge of geology and hydrogeology, drilling technologies, well construction standards and regulations related to their activity and that the equipment they use comply with existing standards. In France, given that less then one thousand companies specialized in drilling operate at the national level, the implementation of such a licensing system should not represent a major challenge for the Government.

Drilling companies would be made liable for damages to third parties or to the environment that could result from non compliance with tube well construction standards. The quality of the construction would be checked after construction through a site inspection, possibly using video cameras to inspect the well. And contractors would not only have general liability insurance but also deposit a cash bond or an irrevocable letter of credit corresponding to the cost of well abandonment – payable to a government agency. Such a system is already implemented in most of the United States of America.

Finally, the current (and ineffective) system of a posteriori declaration of water well should be replaced with a system of permits which should be obtained before drilling, the permit specifying where and when the well will be drilled and each well being given a identification plate. Law enforcement would be strengthened with, one the one hand, an increased random control of contractors and well owners, and, on the other hand, an increase level of sanctions (imprisonment and fines) as it is already the case in most of the states of the USA and the regions of Canada (for instance, unlicensed well drillers were fined $24,000 in Ontario in 2002 and their license revoked).

Regulating the drilling fever through pricing structure

The second approach would consist in charging households with a flat rate tariff for wastewater treatment, instead of the volumetric system currently used. Such a policy, which is already implemented in some French municipalities, would drastically reduce the profitability of boreholes. Figure 8 depicts the evolution of profitability threshold values (median and lower quartile). The profitability threshold (lower quartile) would increase from 225 in the current situation to 350 m^3 /year / household if waste water treatment was charged on a flat rate basis.

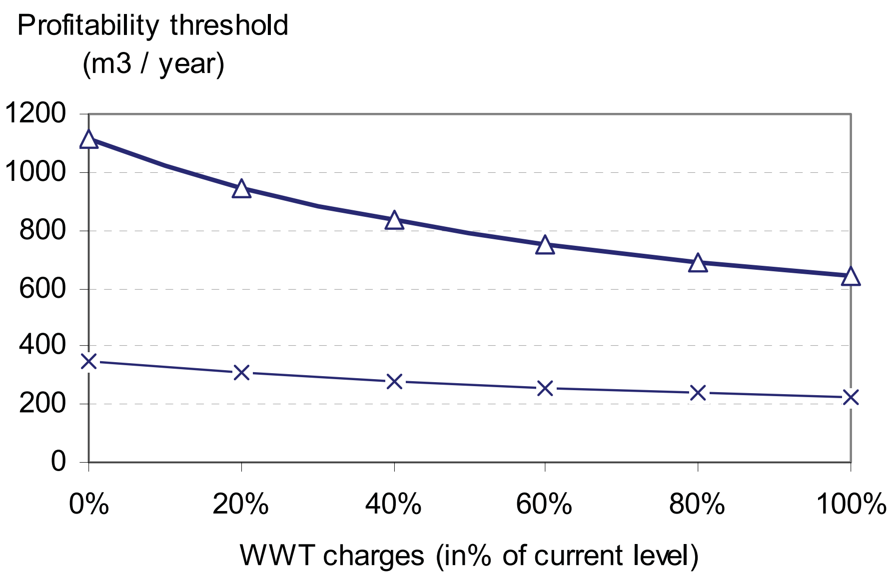


Figure 8: Evolution of profitability threshold with decreasing waste water charges.

VII. CONCLUSION

In this paper, we stress that pricing policies aiming at reducing water demand may have a significant counterproductive impact, as they may encourage the development of private tube wells by households, when natural and economic environment make this option feasible. Interviews conducted at the national and at the local level, as well as simulation made with an economic model have shown that more than 25% of households may own a garden tube well in municipalities where groundwater is easily accessible. In the most favorable hydrogeological and economic contexts (i.e. high drinking water price and shallow groundwater), constructing a tube well can be a profitable option for all households consuming more than 70 cubic meters of water per year for outside uses (garden watering, swimming pool filling, car washing) or for outdoors plus indoor uses such as toilets flushes and washing machine for instance.

Due to the lack of control of drilling companies, the increase of poorly constructed private boreholes generate a significant threat for groundwater, each borehole representing a potential risk of pollution of aquifers. The development of tube wells may also generate a risk of over-exploitation of aquifers in groundwater sensitive areas. And they are creating serious management problems for public water utilities in terms of water demand forecasting and wastewater charges recovery. Finally, the lack of control of groundwater quality pumped through private tube wells may generate a public health problem for households who entirely substitute untreated groundwater to drinking water. The causes and consequences of this phenomenon are not specific to the French context and they have also mentioned in other European (the Netherlands, see [*Meij, et al.*, 2005] and non European countries (Australia).

The paper also shows that the construction of private tube well by households is expected to intensify in the near future for at least two reasons: water price will continue rising, reinforcing economic incentives to drill; and the continuous growth of the drilling market combined with the lack of control of drilling practices by government agencies will result in a fierce competition likely to pull down drilling prices, at the expenses of tube well construction quality. The consequences of such a development would be all the more serious that it is not reversible: once a tube well is constructed, the owner will continue using it as long at it does not needs rehabilitation (usual service life of 20 to 30 years), the marginal pumping cost remaining g very low as compared to any other alternative resource.

To be able to curve the development of private tube wells, the French authorities should urgently strengthen existing rules and regulations related to tube well construction. This would probably rule out of business contractors operating without the appropriate equipment and not following the quality standards, increase market drilling prices and reduce economic incentives for households to drill their own wells. The authorities should also promote the adoption of alternative sewerage service pricing structures enabling to charge tube well owners for the waste water their discharge in the public network. Finally, the development of networks distributing untreated raw water for outside uses could be encouraged to provide households with an economically acceptable alternative to drilling. This third policy option, which was not explored in this paper, would consist in providing households with an access to an alternative untreated water supply cheaper than groundwater obtained through tube wells, when it is possible. This could be achieved through an extension of existing irrigation networks (using surface water resources) to supply houses located in semi-urban areas. Many examples of such combined urban-agricultural water supply systems already exist in Southern France, and they are continuously extending despite high investment needs. They are also being developed in other parts of the world, for instance in Colorado (Sociology Water Lab and Colorado Institute for Irrigation Management, 2003). This option is currently being adopted by public policy makers in the case study area where a pipeline is constructed to supply most of the municipalities of the Montpellier "great belt" urban area with untreated raw water (abstracted in the Rhône River more than one hundreds kilometers to the East). Whether this experiment will be a success depends on the ability of the surface raw water supply company to attract customers more than water well drillers.

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