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Regulating Pollution under Asymmetric Information: The Case of Industrial Wastewater Treatment[1]

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We present in this paper an empirical evaluation of a contract-based environmental regulation under asymmetric information. An imperfect pollution tax results in the necessity of regulating industrials by a contract-based policy, in order to promote a higher level of pollution removal. The local regulatory agency has imperfect information on costs of abatement and must design a feasible mechanism providing incentives for industrials to extend their wastewater treatment plant capacity. The optimal policy consists in regulating only the most efficient industrials in the abatement activity. Empirical evidence reveals that the pollution tax should be more than twice its present level to attain the fully internalizing Pigouvian tax level.

I. INTRODUCTION

It is well recognized that environmental policy may be implemented through a combination of instruments including emission charges, direct controls on emission levels, rewards for pollution removal, and deposit–refund systems (see Xepapadeas [13]). The choice of combined instruments depends essentially on efficiency criteria but also on institutional limitations and legal impediments. In many cases, the range of available instruments is indeed limited by the legislative nature and scope of the pollution control agency. For this reason, the emission tax appears as a prevailing instrument for policy implementation in many instances. Evidence, however, suggests that the effectiveness of emission charges as a single policy instrument may depend crucially on the ability to equate emission tax with marginal social damage [6]. In addition to uncertainty about damage and abatement cost functions, budget-balancing requirements may also limit the ability of the agency to select the Pigouvian tax level.[2] As a result, the agency is not willing to rely upon emission charges only, and uses instruments taking the form of contracts between the agency and individual polluters. Regulating individual polluters by means of contracts provides a flexible way to achieve environmental targets in the presence of imperfect emission tax. Because measurement methods are often very costly to implement, individual monitoring is often discarded and contracts include in most cases only the capital stock to be invested in the abatement plant and a subsidy. Hence, the combination of a presumably imperfect

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[2]This is particularly so in France, where Water Agencies design emission charges on a 5-year basis, after negotiation with industrials' representatives. Emission charges are set according to a budget-balancing institutional requirement, as Water Agencies are zero-profit-making public administrations. Furthermore, the government has often in the past limited significant increases in the pollution tax level, on the ground of antiinflationary measures.

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tax per unit of emission and a contract constitutes a minimal implementation system which is currently employed by many pollution control agencies throughout the world.

As for most regulating policies, however, optimal monitoring of abatement efforts cannot be reached because of informational limitations. The agency has in particular no information on the operating costs of abatement of individual polluters, which are private information to firms. Therefore, a first-best contracting scheme is not possible, and the absence of perfect information necessitates a trade-off between efficiency and incentives in the policy implementation. The regulation of industrial pollution is therefore fully compatible with adverse-selection models, based on the assumption that the industrial has private information on some efficiency (or cost) parameter, which is unknown to the pollution control agency (see Baron and Myerson [3]).

The purpose of this paper is to provide a theoretical explanation for the combined use of emission tax and contracts. The results of the paper are derived under the assumption of an imperfect emission charge and limited information on abatement costs. The main question we address is the relation between the degree of tax imperfection and the contract-based regulation domain. In the case of an optimal emission tax, the external cost of environmental damage is fully internalized by polluters and contracts between the agency and individual polluters are redundant instruments. On the other hand, if the tax imperfection (the gap between the actual and the optimal tax level) is infinite, the role of contracts as regulatory instruments is essential and all industrials should be regulated. Between these two extremes, the degree of imperfection in the pollution tax has a direct impact on the proportion of industrials the agency accepts to contract with.

The paper then presents an empirical evaluation of a contract-based regulation of water pollution, using plant-level data on contracts between a French pollution control agency (Water Agency) and individual polluters. The first objective of the empirical analysis is to evaluate the degree of imperfection in the emission tax. As the gap between the optimal and the actual tax influences directly the regulation domain, it is also possible to estimate the proportion of regulated industrials. The other interesting feature of the empirical analysis presented in the paper is to derive individual abatement functions including industry and plant-specific effects.

The rest of the paper proceeds as follows. Section II presents the model of abatement in the absence of contract regulation. The industrial selects status quo equilibrium levels of capital stock and pollution removal which are typically suboptimal, mainly because abatement costs are too high relative to the emission tax. Section III is concerned with the optimal contracting design proposed by the agency to individual polluters. The agency discriminates among all industrials according to their efficiency in the abatement activity. Because of asymmetric information on abatement costs, the agency has to concede an informational rent to industrials; the implicit trade-off between acceptable levels of abatement and the social costs associated with the rent leads the agency to regulate only the most efficient industrials in the abatement activity. The main result is that there exists a critical value for the abatement cost parameter, depending on the degree of tax imperfection and above which industrials are not regulated. Section IV provides a brief description of the data and Section V presents the estimation method. Estimation results and policy implications are detailed in Section VI. We assess the relative efficiency of industrial sectors in the wastewater treatment activity by specifying a conditional distribution for the variable cost of abatement parameter. To evaluate the consequences of possible changes in the emission tax, we compute expected abatement, capital stock, and total surplus under various tax regimes, using a simulation procedure. Section VII concludes.

II. THE MODEL OF ABATEMENT

Consider a representative industrial facing a unit emission tax p. Pollution removal may be achieved by constructing and operating an external abatement plant. Let Q denote the level of pollution removal, and K and C denote the fixed and variable cost of the treatment plant, respectively. We assume that production and abatement activity are independent, which may be justified by considering that (a) the level of the pollution tax p is not very important and (b) the production cost is far greater than the abatement cost. Hence, the level of the emission tax does not influence the allocation of inputs in the production process. The marginal cost of abatement is assumed to depend on some parameter θ, in that a higher θ corresponds to a less efficient industrial, in terms of abatement.[3] We adopt a Cobb–Douglas specification for the variable cost function:

$$C[\theta, Q, K] = \theta Q^{\alpha_1} K^{\alpha_2}. \tag{1}$$

We assume the following constraints are satisfied

- $C_Q \geq 0$ $C_K \leq 0$;
- $C_\theta \geq 0$: variable cost increases in θ;
- $C_{QQ} \geq 0$ $C_{KK} \geq 0$ $C_{QQ} C_{KK} > (C_{QK})^2$: the cost function is convex;
- $C_{K\theta} > \dfrac{C_{QK} C_{\theta Q}}{C_{QQ}}$ and $C_{\theta Q} > \dfrac{C_{QK} C_{\theta K}}{C_{KK}}$: Spence–Mirrlees conditions

so that we must have

$$\alpha_1 \geq 1, \quad \alpha_2 \leq 0, \quad \theta > 0, \quad \text{and } \alpha_1 + \alpha_2 - 1 > 0.$$

The Spence–Mirrlees conditions ensure that higher values of θ correspond to a greater inefficiency in all directions. An industrial will always be more inefficient with respect to Q and K if the value of the parameter θ is higher. Note also that the Spence–Mirrlees conditions usually produce second-order conditions in adverse-selection models which are easier to handle.

The profit of the industrial in the abatement activity is

$$\Pi = pQ - C(\theta, Q, K) - K.$$

When not regulated, the industrial maximizes his profit with respect to Q and K, which yields the status quo solutions (Q^0, K^0) to the system:

$$p = C_Q(\theta, Q^0, K^0) \tag{2}$$

$$1 = -C_K(\theta, Q^0, K^0). \tag{3}$$

[3] The parameter θ will at times be referred to as the "type" of the industrial.

In order to derive comparative-static results, we differentiate both equations with respect to θ. Using the Spence–Mirrlees and the convexity conditions given above, we have that

$$\frac{dQ^0}{d\theta} \leq 0 \qquad \frac{dK^0}{d\theta} \leq 0.$$

Hence, industrials with a high marginal cost of abatement invest relatively less in the treatment plant, and consequently reduce their effluent emissions by a lower amount. Furthermore, it is easy to show that Q^0 and K^0 are increasing functions of p. In the case of an imperfect pollution tax, the equilibrium solution Q^0 will be too low compared to the optimal level (from a social viewpoint). The pollution control agency must therefore design a supplementary regulatory instrument in order to compensate for insufficient levels of pollution removal. By designing a contracting scheme encouraging industrials to invest more than in the status quo situation, marginal cost of abatement is bound to decrease, hence fostering an increased abatement level.

III. THE OPTIMAL CONTRACTING SCHEME

The problem of the pollution control agency is to design an optimal contracting mechanism, so that the industrial prefers the contract-based relationship to the status quo situation. In other words, his profit must be higher, given the fact that levels of abatement and capital are more important and that a transfer (i.e., a subsidy) is granted.

Consider the perfect-information case when the agency knows the value of θ. Letting $S(Q)$ denote the consumers' utility for abatement, an increasing and concave function of the abated quantity, $Q(\theta)$, the agency maximizes a weighted sum of the consumers' net surplus and the profit of the industrial

$$\beta[S(Q) - pQ - T] + (1 - \beta)[pQ - C[\theta, Q, K] - K + T] \tag{4}$$

under the conditions

$$\Pi \geq \Pi^0 \tag{5}$$

$$\Pi = pQ - C(\theta, Q, K) - K + T \tag{6}$$

$$p = C_Q \tag{7}$$

$$K \geq K^0, \tag{8}$$

where T is the subsidy from the agency to the industrial. β is an arbitrary weight which represents the preferences of the agency. β is assumed to belong to the interval $(\frac{1}{2}, 1]$ if the agency values consumers more than the industrial (see Baron [5] for a discussion of the choice of a regulatory objective). Because β is greater than 0.5, the agency favors consumers and imposes the profit of the industrial to be equal to the status quo one, i.e., $\Pi = \Pi^0$. This is achieved by setting $T = \Pi^0 - pQ + C + K$. The problem of the agency becomes

$$\max \beta[S(Q) - C - K] + (1 - 2\beta)\Pi^0$$
$$p = C_Q.$$

Let Q^* and K^* denote, respectively, the abatement and capital stock solutions under perfect information. The perfect-information solution (Q^*, K^*) is obtained by solving

$$S_Q = p - (C_K + 1)\frac{C_{QQ}}{C_{QK}} \tag{9}$$

$$p = C_Q. \tag{10}$$

Because C_{K+1} becomes positive, the capital stock K^* is greater than K^0 (obtained in the status quo case). Furthermore, the subsidy is designed so that no rent is left to the industrial. This is of course possible only because the agency knows the true value of θ.

When the agency has no information on the efficiency parameter θ, it is not able to allocate each firm a capital stock level according to its performance in terms of abatement. Consequently, the contract proposed to the industrial must provide incentives for the latter to reveal his true "type" θ; this is referred to as the "incentive-compatibility" constraint in the literature on incentives. The agency will therefore offer a menu of policies $(K(\theta, T(\theta))$ and let the industrial choose the combination he prefers, given his true type θ.[4]

In terms of the principal–agent paradigm, the agency acts as a regulator by contracting with the industrial. The problem of regulating pollution under asymmetric information has already received much attention in the literature; the framework of our model is a slightly different version of Baron [4]. The agency is assumed to have prior information about θ represented by a density function f and a distribution function F on the domain $[\underline{\theta}, \bar{\theta}]$.

The problem of the agency is

$$\max W = \int_{\underline{\theta}}^{\bar{\theta}} \{\beta[S[Q(\theta)] - pQ(\theta) - T(\theta)] + (1 - \beta)\Pi(\theta)\} f(\theta)\, d\theta \tag{11}$$

such that

$$p = C_Q[\theta, Q(\theta), K(\theta)]$$
$$K(\theta) \geq K^0(\theta)$$

under the participation constraints

$$\begin{cases} \Pi(\theta) \geq \Pi^0(\theta), & \forall\theta \in [\underline{\theta}, \bar{\theta}] \\ \Pi(\theta, \theta) \geq \Pi(\theta, \tilde{\theta}), & \forall\theta \in [\underline{\theta}, \bar{\theta}] \quad \forall\tilde{\theta} \in [\underline{\theta}, \bar{\theta}]. \end{cases}$$

$\tilde{\theta}$ is the report of a type by the industrial and $\Pi^0(\theta)$ the profit obtained in the status quo situation. $\Pi(\theta, \tilde{\theta})$ is the profit of the industrial when he reports a type $\tilde{\theta}$

[4]See, for example, Besanko and Sappington [7].

while his true type is in fact θ; it is defined by

$$\Pi(\theta,\tilde{\theta}) = \max_{Q} pQ - C[\theta, Q, K(\tilde{\theta})] - K(\tilde{\theta}) + T(\tilde{\theta}).$$

The second constraint indicates that it is not in the industrial's interest to report a type $\tilde{\theta}$ different from his real one, θ.

The objective of the agency is to promote an increase in the pollution removal level (or equivalently, an increase in the capital stock level, because Q and K move together; see the preceding section), while maximizing the total surplus. However, the agency is likely to face an informational rent which is socially costly because of the opportunity cost of public funds. It is therefore necessary for the agency to discriminate among firms, and to regulate only a fraction of all industrials.

We state the following proposition and corollary, the proofs for which are omitted at the Editor's request. Proofs are available from the author upon request.

PROPOSITION 1. *Assume S is linear in Q, with $S_Q = p^*$. We suppose $(F(\theta)/f(\theta))(1/\theta)$ is nondecreasing in θ. Then there exists a critical value θ^*, solution to*

$$\frac{1-2\beta}{\beta}\frac{F(\theta)}{f(\theta)}\frac{1}{\theta} = \alpha_1\left(1 - \frac{p^*}{p}\right),$$

such that

(a) *For $\theta < \theta^*$, the industrial is regulated and the optimal contract (Q^{**}, K^{**}) is given by the system*

$$\frac{-\alpha_2}{\alpha_1 - 1} Q^{\alpha_1} K^{\alpha_2 - 1}\left[\theta\left(\frac{p^*}{p}\alpha_1 - 1\right) + \frac{1-2\beta}{\beta}\frac{F(\theta)}{f(\theta)}\right] = 1 \qquad (12)$$

$$p = \theta\alpha_1 Q^{\alpha_1 - 1} K^{\alpha_2}, \qquad (13)$$

(b) *For $\theta \geq \theta^*$, the industrial is not regulated and we have the status quo solutions (Q^0, K^0).*

COROLLARY 1.

(a) *The regulatory domain increases when p decreases*

$$p^*/p \to +\infty \Leftrightarrow \theta^* \to \bar{\theta}$$

and

$$p^*/p \to 1 \Leftrightarrow \theta^* \to \underline{\theta}.$$

(b) For every θ, the abatement solution under imperfect information, Q^{**}, is always lower than the abatement level in the perfect-information case, Q^*.

This proposition exhibits the influence of the tax imperfection on the regulation domain. When the actual tax is very different from the optimal level p^*, the regulation domain enlarges to include less and less efficient industrials. On the contrary, if p is sufficiently close to $p^* = S_Q$, i.e., when the actual tax tends to the Pigouvian level, we obtain the status quo situation with optimal levels of abatement and capital and the regulation domain becomes empty.

The imperfection in the pollution tax system plays a fundamental role in the determination of the regulation domain. If the tax level is very far from the optimal value (in the Pigouvian sense), the agency compensates for this imperfection by proposing contracts to a majority of industrials. On the other hand, in the situation where the gap between the actual and the optimal tax is very small, it is not necessary to regulate in the sense of larger incentives to increase pollution removal any further. The role of contracts as pollution control policy instruments becomes negligible.

With an objective of a significant reduction in the ambient pollution level, the optimal policy consists in contracting only with the most efficient industrials. One rationale for this can be found from the literature on incentives. Although inefficient firms are characterized by a higher marginal cost of abatement, their participation in the regulatory relationship is not very costly in terms of informational rent. The problem is that, in order to avoid "good" types reporting as "bad" ones, the informational rent must be increasing in the efficiency parameter (or, equivalently, decreasing in θ), the less efficient of all industrials receiving a zero rent. As a result, when less and less efficient industrials are regulated, the informational rent granted to efficient firms increases rapidly and causes the contract-based regulation to be very costly. In other words, inefficient industrials are not discarded from the regulatory relationship because of their poor performance in the abatement activity, but because the regulation of efficient firms would prove too costly.

This result is interesting when considering the possible alternative strategies for implementing environmental policy: (a) Encourage very efficient industrials to achieve the best results in pollution removal by designing important abatement capacities; (b) Promote a general increase in efficiency in the wastewater treatment activity, by allowing poorly efficient industrials to invest in a more efficient abatement equipment. Clearly, our theoretical result is in favor of choice (a).

Figure 1 presents the theoretical capital stock in the three situations considered: status quo (K^0), perfect information (K^*) and imperfect information (K^{**}). For θ above θ^*, industrials are not regulated and K^{**} coincide with K^0; furthermore, the perfect-information capital stock K^* is always above K^0 and K^{**}. In

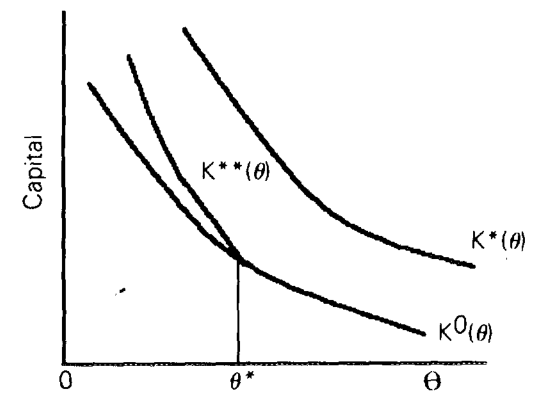

FIG. 1. Capital stock solutions. K^0, status quo; K^*, perfect information; and K^{**}, imperfect information.

logarithmic form, the optimal abatement and capital stock solutions under asymmetric information (Q^{**}, K^{**}) are, from Eqs. (12) and (13)

$$\log(Q^{**}) = \frac{1}{\alpha_1 + \alpha_2 - 1}\Bigg\{(\alpha_2 - 1)\log(\theta) + (\alpha_2 - 1)\log(\alpha_1) - \alpha_2 \log\left[\theta(\gamma\alpha_1 - 1) + \frac{1-2\beta}{\beta}\frac{F(\theta)}{f(\theta)}\right] - \alpha_2 \log\left(\frac{-\alpha_2}{\alpha_1 - 1}\right) - (\alpha_2 - 1)\log(p)\Bigg\} \tag{14}$$

$$\log(K^{**}) = \frac{1}{\alpha_1 + \alpha_2 - 1}\Bigg\{-\alpha_1 \log(\theta) - \alpha_1 \log(\alpha_1) + (\alpha_1 - 1)\log\left[\theta(\gamma\alpha_1 - 1) + \frac{1-2\beta}{\beta}\frac{F(\theta)}{f(\theta)}\right] + (\alpha_1 - 1)\log\left(\frac{-\alpha_2}{\alpha_1 - 1}\right) + \alpha_1 \log(p)\Bigg\}, \tag{15}$$

where $\gamma = p^*/p$ is a parameter measuring the gap between the optimal and the actual emission tax. This system forms the basis of the estimation procedure detailed in Section V.

IV. DESCRIPTION OF THE DATA

Data used for estimation were made available from the Adour–Garonne Water Agency (southwest France). The file containing the description of individual contracts was merged with the one relative to effluent emissions and emission charges for the 1986–1992 period. The number of observations is 185.

Capital stock K and subsidy T. The contract file contains information on the capital stock invested in the abatement plant. We restrict the analysis to external treatment ("end-of-pipe-abatement") plants, discarding contracts concerned with internal processes, because in that case the level of pollution removal cannot be measured. In some instances, an industrial benefits from several contracts during the period; successive investments and subsidies are then aggregated when they correspond to the same treatment plant and complement the first investment.

The agency's financial support can take different forms: direct subsidies, short-term loans with a 0.5% interest rate, or long-term loans with a 3% interest rate. To make all contracts comparable, we convert loans into direct subsidies by computing the difference in interest payments with the actual market rate. Both investments and subsidies are deflated using the 1991 price index.

Pollution removal level Q and pollution tax p. The Water Agency data set contains yearly levels of effluent emissions, both before and after treatment. Five categories of pollutants are recorded: biological oxygen demand (BOD), suspended solids (SS), nitrogen (N), phosphorus (P), and absorbable organic halogens (AOX). Because our model would become very complicated if these five pollutants were dealt with simultaneously, we choose to retain BOD as a single index of pollution,[5] as it accounts on average for about 70% of total emission charges. The level of pollution removal is computed for each industrial as the difference between gross and net effluent emissions, 1 year after the contract is signed by the industrial. Average levels of abated pollution for each plant were compared to our pollution index, to check that retaining only 1 year of abatement activity is sufficient, as the series are indeed stationary. The unit tax p is the emission tax on BOD corresponding to the same year as the pollution index; it is also deflated using the 1991 price index.

Exogenous variables. Additional data required for estimation are exogenous variables used in the specification of the conditional mean of θ, as well as instrumental variables. In order to account for industry-specific effects, we use industry dummies to compute the conditional mean of the efficiency parameter. Four industrial sectors are considered: chemicals, iron and steel, manufactured food, and wines-and-spirits. To account for a pollution-scale effect, BOD emissions will also be incorporated into the conditional mean of the efficiency parameter. There are many other exogenous variables available, which are used in the estimation procedure as instrumental variables. Most are geographical and environmental dummies, whose definition is

- ENV, Environment concerned with the effluent emissions; ENV1, Normal river; ENV2, Ground water; ENV3, Source; ENV4, Underground water; ENV5, Lake or pond; ENV6, Sea; ENV7, Ground; ENV8, Lagoon.

- ZONE, Geographical zone; ZONE1, Zone with an urgent need for pollution removal; ZONE4, Garonne valley; ZONE5, Zone of "upper Tarn"; ZONE6, Above Charente; ZONE7, Aveyron.

- QUAL: Ambient quality of the water stream; 1 if the water quality is good and 0 otherwise.

V. ESTIMATION METHOD

The proposition in Section III implies that observations on contracts are only available for regulated industrials, whose parameter θ is lower than the critical value θ^*. As a consequence, it is necessary to take such a truncation into account in the estimation process, to avoid the selection bias due to the fact that industrials in the status quo situation are not observed. It is convenient to assume θ is log–normally distributed, for several reasons. First, the log–normal distribution is traditionally employed when variables defined on the positive line are modeled. Second, this choice is convenient because parameter θ appears mostly in logarithmic form in the equations to be estimated. Third, moments of the distribution are easy to compute and the assumption of a non-decreasing ratio $(1/\theta)(F(\theta)/f(\theta))$ is satisfied for this distribution.

The mean of $\log(\theta)$ is conditioned with respect to exogenous variables which presumably influence the industrial's level of efficiency: four industry dummies and a pollution-scale indicator (biological oxygen demand, BOD). The conditional

[5]A possibility would be for instance to construct a pollution index from a linear combination of the five pollutants. The problem with this approach is that the structure of pollution is likely to be different among industrials.

expectation of $\log(\theta)$ for industrial $i, i = 1, \ldots, N$ reads

$$E[\log(\theta_i)|Z_i] = Z_i'\lambda,$$

where Z_i is the vector of exogenous variables (including an intercept) and λ the associated vector of parameters.

The estimation step proceeds as follows. First, we estimate Eq. (13) to get estimates of the conditional distribution of $\log(\theta)$. This equation reads, in logarithmic form

$$\log(Q_i) = (\alpha_1 - 1)^{-1}\{\log(p) - \log(\alpha_1) - \alpha_2 \log(K_i) - Z_i'\lambda\} + u_i \quad (16)$$

where $u_i = -(\alpha_1 - 1)^{-1}[\log(\theta_i) - Z_i'\lambda]$ is the error term.

As mentioned above, it is necessary to deal with the truncation bias. To this end, we use the traditional Tobit model, by noting that the truncation term (Mill's ratio in the literature on limited-dependent variables) has a simple form in the normal case

$$E[\log(\theta_i) - Z_i'\lambda|\log(\theta_i) - Z_i'\lambda < \log(\theta_i^*) - Z_i'\lambda]$$
$$= \sigma E[\varepsilon_i|\varepsilon_i < (\log(\theta_i^*) - Z_i'\lambda)/\sigma] = -\sigma\frac{\phi(X^*)}{\Phi(X^*)},$$

where ε_i is a standard normal variate with density function ϕ and distribution function Φ, and $X^* = (\log(\theta_i^*) - Z_i'\lambda)/\sigma$. From the definition of the conditional expectation, it is immediate that critical values are in fact different among industrials. In fact, each critical value θ_i^* may be identified by the relation

$$\log(\theta_i^*) = Z_i'\lambda + \sigma X^*.$$

X^* has a very interesting interpretation: its associated probability represents the proportion of regulated industrials, which is independent from individual characteristics (industry sector, geographical localization, etc.). The two-stage nonlinear least-squares procedure is employed (see Amemiya [1, 2]) to yield consistent parameter estimates of α_1, α_2, X^*, and λ. It necessitates in particular constructing a matrix of instrumental variables. Note also that σ is not identified and is normalized to 1.

The second step in the estimation process consists in estimating the structural parameters α_1, α_2, β, and γ from the contract Eqs. (14) and (15) in reduced form, using parameter estimates for the distribution of θ obtained in the first stage. As θ is unobservable and appears in a nonlinear way (it may be considered a latent variable), standard econometric methods are not feasible.

Recent developments in econometric theory provide useful methods for estimating nonlinear equations containing latent variables. These methods are based on simulation techniques, consisting in integrating expressions without analytical solution with respect to the density of the unobservable variable, where the integral is approximated by simulation (see Gouriéroux and Monfort [8], Pakes and Pollard [12], and McFadden [10]).

Let us write the system (14)–(15) in a compact form

$$\log(Q_i) = G_1(X_i, \theta_i; b)$$
$$\log(K_i) = G_2(X_i, \theta_i; b),$$

where X_i is the vector of exogenous variables and b the vector of parameters.

By introducing the truncation condition, we have the conditional expectations

$$E[\log(Q_i)|\theta_i < \theta_i^*] = \frac{\int_{\underline{\theta}}^{\theta_i^*} G_1(X_i, \theta; b) f(\theta)\, d\theta}{\text{prob}(\theta_i < \theta_i^*)} \tag{17}$$

$$E[\log(K_i)|\theta_i < \theta_i^*] = \frac{\int_{\underline{\theta}}^{\theta_i^*} G_2(X_i, \theta; b) f(\theta)\, d\theta}{\text{prob}(\theta_i < \theta_i^*)}. \tag{18}$$

Integrals $\int_{\underline{\theta}}^{\theta_i^*} G_j(\cdot) f(\theta)\, d\theta$, $j = 1, 2$ can be approximated numerically by simulation, while denominators are simply $\text{prob}(\theta_i < \theta_i^*) = F(\theta_i^*)$. As the θ_i's must be positive and lower than θ_i^*, it suffices to generate simulated values on the compact set $[0, \theta_i^*]$. For each observation i, we generate a S-vector of draws $\{u_i^s\}$, $s = 1, \dots, S$ from the uniform density function $h(u_i^s)$ on $[0, 1]$ to obtain simulated values θ_i^s as

$$\theta_i^s = \theta_i^* u_i^s \qquad i = 1, \dots, N \qquad s = 1, \dots, S,$$

where S is the number of simulations. The system of equations becomes

$$\log(Q_i) = \frac{1}{F(\theta_i^*)} \frac{1}{S} \sum_{s=1}^{S} G_1(X_i, \theta_i^s(u_i^s); b) \frac{f(\theta_i^s(u_i^s))}{h(u_i^s)} + u_i^1 \tag{19}$$

$$\log(K_i) = \frac{1}{F(\theta_i^*)} \frac{1}{S} \sum_{s=1}^{S} G_2(X_i, \theta_i^s(u_i^s); b) \frac{f(\theta_i^s(u_i^s))}{h(u_i^s)} + u_i^2, \tag{20}$$

where u_i^1 and u_i^2 are residuals with zero mean and variance–covariance matrix Ω. The simulated generalized method of moments (simulated GMM) yields consistent and asymptotically normal parameter estimates, even when the number of simulations is small. The vector of parameters λ is already estimated from the first state; it can be replaced in the system above.

The simulated GMM criterion to be minimized is

$$\sum_{i=1}^{N} (u_i' \otimes W_i) \left[\sum_{i=1}^{N} (W_i' W_i) \otimes \hat{\Omega} \right]^{-1} \sum_{i=1}^{N} (u_i \otimes W_i'),$$

where $u_i = (u_i^1, u_i^2)'$, W_i is a vector of instruments and $\hat{\Omega}$ is a consistent estimator of Ω. This suggests to use a two-step procedure consisting in first estimating the variance–covariance matrix of errors and then replacing Ω by its estimate in the simulated GMM criterion.

In practice, the estimation algorithm is the following.

- Starting from initial values for parameters, we find X^* as the solution to

$$\frac{(1-2\beta)}{\beta}\frac{\Phi(X^*)}{\phi(X^*)} = \alpha_1(1-\gamma),$$

by noting that

$$\frac{1}{\theta}\frac{F(\theta)}{f(\theta)} = \frac{\Phi(\log(\theta))}{\phi(\log(\theta))}.$$

- Critical values $\log(\theta_i^*)$ are computed as $\log(\theta_i^*) = Z_i'\lambda + \sigma X^*$.
- Simulated values θ_i^s are generated from u_i^s: $\theta_i^s = u_i^s\theta_i^*$.
- Conditional expectations are computed by averaging simulated expressions as in Eqs. (19) and (20) and the simulated GMM is computed.
- This procedure is repeated until convergence.

VI. ESTIMATION RESULTS

Equation (16) is first estimated by two-stage nonlinear least-squares, incorporating the correction term for truncation defined above. This provides consistent estimates of parameters in the conditional mean of $\log(\theta)$; the variance σ^2 is not identified at this stage and is normalized to 1. Instrumental variables used are COD2, COD4, COD6, COD7, QUAL1, ENV1, ENV7, BOD, ZONE1, and ZONE6. The choice of these instruments follows the optimal two-step procedure described in Amemiya [2].[6]

The second step consists in estimating structural parameters β, γ, and σ by the simulated GMM method. Parameters in the cost function α_1 and α_2 are also consistently estimated, using estimates from the first stage as starting values for the minimization algorithm. Because σ is now identified, parameter X^* is obtained numerically as described in the preceding section; although consistently estimated, the estimated value of X^* obtained from the first stage is of course different, because σ was normalized to 1. The number of simulations is set to 100 and instrumental variables are ZONE1, COD2, COD4, ENV7, and BOD.

Table I presents final parameter estimates. It was not necessary to impose constraints on parameters ($\alpha_1 > 1$, $\alpha_2 < 0$, $\alpha_1 + \alpha_2 - 1 > 0$). Interesting implications may be drawn from the magnitude of parameters in the conditional mean of the efficiency measure,[7] $\log(\theta)$ (recall that an industrial is relatively less efficient in the treatment activity when the associated conditional mean $Z_i'\lambda$ is higher). The chemical industry appears to be the most efficient in the wastewater treatment

[6] Other exogenous variables related to the environment and the geographical zone were also incorporated in the conditional expectation, but they were not retained since they proved to be nonsignificant.

[7] The Hausman exogeneity test statistic is computed to check for the endogeneity of the capital stock K. Under the null hypothesis of exogeneity, the test statistic is equal to 5.64, which allows to reject the exogeneity hypothesis for the capital stock.

TABLE I
Parameter Estimates

Structural parameters	
α_1	3.6118
	(5.79)
α_2	−0.4806
	(−2.37)
β	0.7364
	(8.36)
γ	2.2723
	(4.67)
Conditional mean parameters	
Constant	3.3056
	(1.23)
Iron and Steel	0.8680
	(2.18)
Chemicals	−0.4013
	(−2.37)
Wines-and-spirits	−0.2974
	(−2.35)
Manufactured food	−0.2948
	(−3.36)
Plant size (BOD)	−0.1584
	(−2.35)
Standardized bound X^*	0.9839
	(0.14)
σ	2.1224
	(9.62)

Note. t statistics are in parentheses. Parameters of the conditional mean of $\log(\theta)$ are estimated from Eq. (16) (method used: nonlinear two-stage least-squares). Parameters α_1, α_2, β, γ, and σ are estimated from the reduced-form eqs. (14) and (15) (method used: simulated GMM). Number of simulations for simulated GMM: 100.

activity, on the period considered, while the wines-and-spirits and manufactured food industries are less efficient. Finally, the iron and steel industry is by far the less efficient of all.

A possible explanation is that chemical plants represent such an important potential in terms of toxic wastes that the equipment specially designed for them has a long history, which could account for low operating costs, using an argument of economies of scale in the wastewater treatment industry. The French Ministry of Environment was recording an important effort of the chemical industry in the abatement activity from 1980 to 1986, whereas the abatement activity of the food industry was stagnant [11]. Our results confirm the satisfactory performance of the chemical industry and indicate that firms in the food industry have, on average, succeeded in operating wastewater treatment plants more efficiently.

Variable BOD has a negative coefficient, which indicates that wastewater treatment is less costly for industrials with important effluent emissions. Consequently, larger plants are more efficient and benefit from significant economies of scale.

Estimated value of β is 0.7364 and the ratio of the optimal to the actual pollution tax is 2.2723. The standard error for this parameter is 0.48, allowing one to reject the null hypothesis $p^* = p$ at the usual 5% level. From estimated parameter values, X^* is 0.4852, which represents a proportion of regulated industrials of 68.62% regardless of the pollution scale and industrial sector.

We then use estimated parameters to construct the theoretical subsidy function. Differentiating the industrial's profit with respect to his report $\tilde{\theta}$ yields:

$$[p - C_Q]\frac{dQ}{dK}\frac{dK}{d\theta} - [C_K + 1]\frac{dK}{d\theta} + \frac{dT}{d\theta} = 0$$

so that

$$\frac{dT}{d\theta} = [1 + C_K]\frac{dK}{d\theta}, \qquad \forall\theta.$$

The above expression needs to be integrated, using for Q and K the reduced-form equations estimated above. We have

$$T(\theta) = K(\theta) - K(\theta^*) - \int_{\theta}^{\theta^*} C_K \frac{dK}{d\theta_0}\, d\theta_0.$$

We compute for each industrial the theoretical subsidy by numerical integration; the critical value θ^* is computed for each industrial with the formula

$$\theta_i^* = \exp(Z_i'\lambda + \sigma X^*).$$

Figure 2 presents both actual and theoretical subsidies (logarithmic scale). Some contracts characterizing very efficient firms have less important actual subsidies than predicted by the model.

Interesting policy implications may be derived from our results. The basic instrument the agency can use to promote higher abatement levels is of course the emission tax. According to our estimate of γ, the unit tax should be twice its present level to provide industrials with enough incentives for reducing pollution to a socially acceptable level without any contract-based regulation. The direct effect of increasing the emission tax may be evaluated by considering the reduced-form equation (15) for Q. The price elasticity of abatements is $(1 - \alpha_2)/(\alpha_1 + \alpha_2 - 1) = 0.6947$ using our estimates. Nevertheless, this price elasticity is not an adequate instrument for assessing the effect of changes in the tax level on total abatement, because the regulation domain is modified as the ratio of the optimal tax over the actual one varies. The price elasticity computed above gives only an indication corresponding to industrials who already participate in the regulatory relationship. In order to evaluate the implications of tax changes, we adopt a simulation strategy described as follows.

Possible changes in the level of the emission tax with respect to the actual situation are represented by a grid of values from -50 to 50%. Each percent change in p implies a different parameter γ and in turn, a new critical value θ^* to be computed. From estimates presented in Table I it is possible to simulate values

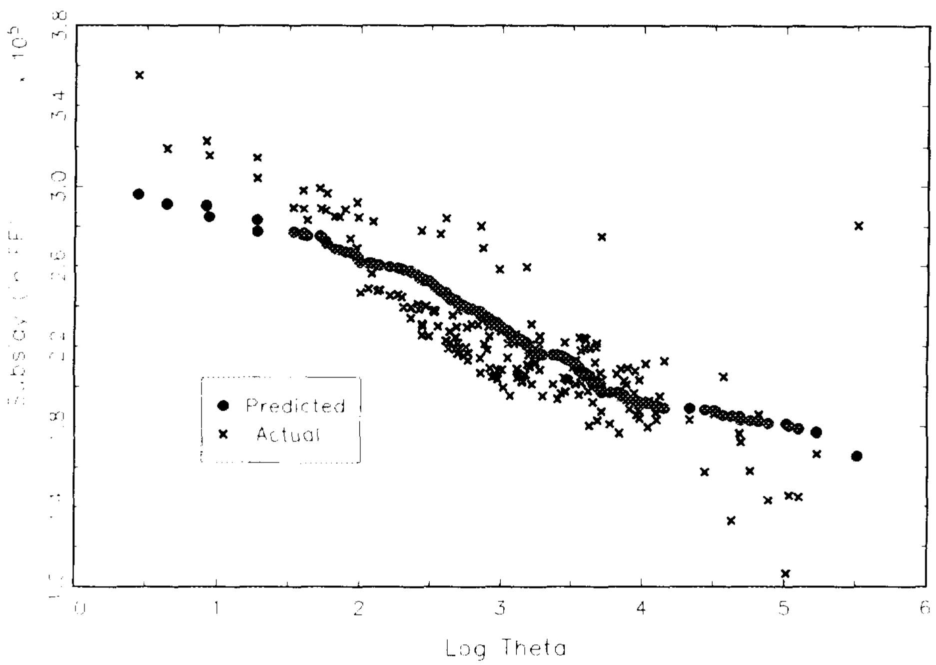

FIG. 2. Actual and predicted subsidies.

for θ, using nonconditional moments of the distribution.[8] For each change in p, we draw 1000 simulated θ's and test whether individual values are lower than the critical value, θ^*. For θ's below the critical value, the reduced-form equations (15) and (16) are employed; when θ is above θ^*, the status quo equations are used for computing Q and K.

Total surplus (consumers' net surplus and industrials' profit) is also simulated with this procedure, to evaluate the welfare implications of possible tax changes. The fact that the contract-based regulation provides a significant reduction in effluent emissions has of course a positive effect on consumers' utility. Industrials are also better off, because their profits are at least equal to their status quo profits. On the other hand, transfers granted to firms reduce the consumers' net surplus. It is therefore difficult to assess the overall gain from the contract-based regulation without using a simulation approach as the one developed here. Total surplus (TS) is computed as $\beta \text{CS} + (1 - \beta)\Pi$, where CS is the consumers' net surplus (consumers' utility minus payments to industrials); $(p^* - p)Q - T$ and Π represents industrials' profit, $pQ - C - K + T$. Averaging the quantities defined above produces the expected abatement, capital stock, and surplus levels for all changes in the tax p.

Table II presents the variations in the expected abatement and capital stock levels, as well as the variation in the total surplus, with respect to the actual situation (where $\gamma = 2.27$). It can be seen from this table that the levels of

[8]The nonconditional expectation of $\log(\theta)$ is computed by averaging conditional means over all industrials in the sample. Employing conditional expectations in the simulations would prove difficult, because plant-specific variables (pollution scale, industrial sector) are of course unknown.

TABLE II

Simulated Welfare Implications of a Change in the Tax Level

Tax change (%)	γ	Regulation domain (%)	Change in Q (%)	Change in K (%)	Change in TS (%)
−50	4.54	96.40	−81.89	−78.58	−75.37
−40	3.78	90.40	−71.52	−67.38	−63.35
−30	3.24	84.00	−58.32	−53.78	−49.35
−20	2.83	76.00	−42.09	−37.89	−33.78
−10	2.52	70.40	−22.69	−19.89	−17.15
−5	2.39	68.40	−11.76	−10.17	−8.60
0	2.27	66.40	0	0	0
5	2.16	62.40	12.38	10.62	8.62
10	2.06	58.40	26.01	21.64	17.17
20	1.89	52.00	55.48	44.73	33.65
30	1.74	47.20	88.47	68.97	48.73
40	1.62	44.40	125.06	93.96	61.59
50	1.51	42.00	165.24	119.43	71.56

Note. All variations are computed with respect to the actual situation ($\gamma = 2.27$). Total surplus (TS) is computed as β CS + $(1 - \beta)\Pi$, where CS is the consumers' net surplus (consumers' utility minus payments to industrials), $(p^* - p)Q - T$ and Π represents industrials' profit: $pq - C - K + T$.

abatement and capital stock are much more sensible to an increase than to a reduction in the tax level; for example, abatement drops by about 58% when p is reduced by 30%, whereas it rises by 88% when p increases by 30%. As expected, an increase in the emission tax leads to a reduction of the regulation domain: with a 50% increase, 42% of industrials participate in the regulatory relationship, compared to 66% in the actual situation. In contrast, a reduction of 50% in the level of the tax has a dramatic effect on the agency's policy, since about all industrials (96%) are regulated. It is interesting to note that total surplus (TS) responds rather symmetrically to changes in the level of the tax. With positive variations in the tax level, the regulation domain reduces and includes relatively more efficient industrials. As a result, the number of contracts diminishes and the informational rent to firms is reduced. Although these simulation results need to be taken with caution, they provide nevertheless insights on the social gain which could be achieved with even a slightly higher tax on emissions.

VII. CONCLUSION

In this paper, we estimated a model of industrial water pollution regulation under asymmetric information. In the presence of imperfect pollution tax, pollution removal levels are less than what would be achieved with an optimal tax system. The pollution control agency has therefore to compensate for this by implementing a contract-based regulatory scheme. Such a policy is aimed at providing incentives for industrials to invest in more important treatment capacities than in the no-regulation situation, in order to reduce their marginal cost of abatement. The contracts must however be designed in such a way that pollution removal levels are higher, given that industrials' efficiency is private information.

In the context of asymmetric information, a rent has to be granted, which becomes more and more costly as less efficient industrials are regulated. For this reason, the agency selects only the most efficient industrials to participate in the regulatory relationship.

Our estimation results provide some insights about the dependence of the individual types, representing broadly a measure of efficiency, with respect to plant-specific variables. It is found in particular that industrials in the chemical industry are more efficient in their abatement activity than firms in the iron and steel, manufactured food, and wines-and-spirits industries. The actual pollution tax level is found to be only 50% of the Pigouvian level. The pollution control agency clearly promotes reduction in ambient pollution level by more efficient industrials, by imposing relatively higher capital stock levels. The financial burden for efficient industrials is also compensated for by granting relatively more important investment subsidies.

A possible extension would be to make our model less restrictive, by incorporating the water input as an endogenous variable in the problem of the industrial. Polluters would then be faced with a multidimensional optimization problem, with the effluent concentration and the quantity of water used for production as input variables. A major difficulty with such an approach is that the profit of individual industrials in their production activity is unknown, although it could be represented using an indirect profit function having the water input as the single argument.

REFERENCES

1. T. Amemiya, The nonlinear two-stage least-squares estimator, *J. Econometrics* **2**, 105–110 (1974).
2. T. Amemiya, "Advanced Econometrics," Harvard Univ. Press, Cambridge (1985).
3. D. P. Baron and R. B. Myerson, Regulating a monopolist with unknown costs, *Econometrica* **50**, 911–930 (1982).
4. D. P. Baron, Regulation of prices and pollution under incomplete information, *J. Public Econom.* **28**, 211–231 (1985).
5. D. P. Baron, Design of regulatory mechanisms and institutions, *in* "Handbook of Industrial Organization" (R. Schmalensee and R. Willig, Eds.), North-Holland, pp. 1347–1448 (1989).
6. W. J. Baumol and W. E. Oates, "The Theory of Environmental Policy", Cambridge Univ. Press, Cambridge, UK (1988).
7. D. B. Besanko and D. E. M. Sappington, "Designing Regulatory Policy with Limited Information," Fundamentals of Pure and Applied Economics, Vol. 20. Harwood Academic, Reading, UK (1987).
8. C. Gouriéroux and A. Monfort, Simulation based inference in models with heterogeneity, *Ann. Econom. Statist.* **20/21**, 69–107 (1991).
9. R. Guesnerie and J. J. Laffont, A complete solution to a class of principal-agent problems with an application to the control of the self-managed firm, *J. Public Econom.* **25**, 329–369 (1984).
10. D. McFadden, A method of simulated moments for estimation of discrete response models without numerical integration, *Econometrica* **57**, 995–1026 (1989).
11. Ministère de l'Environnement, "Etat de l'environnement," La Documentation Française, Paris (1987).
12. A. Pakes and D. Pollard, Simulation and the asymptotics of optimization estimators, *Econometrica* **57**, 1027–1057 (1989).
13. A. P. Xepapadeas, Environmental policy under imperfect information: Incentives and moral hazard, *J. Environ. Econom. Management* **20**, 113–126 (1991).