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Demand Effects and Social Welfare of Water Metering in East Anglia

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Contents

I Introduction

In England and Wales, water companies are abstracting about a half of total freshwater resources (Environment Agency, 2008a), which are projected to increase in order to feed the growing populations. On the other hand, scopes to increase water supply in the future are getting narrower given the environmental constraints including the climate change.

In particular, East Anglia region, where population density is high relative to water availability, may face severer water stresses in the future. This implies putting more pressure to the freshwater environment, as more abstractions at water

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works would lead to fewer flows in downstream rivers and more discharges from sewage works, which are normally more polluted than the original source water.

It is therefore essential for water regulators to encourage households to save water, in order to mitigate such environmental pressures. One of sensible ways to achieve this is to implement "economic incentive" schemes that encourage households to save water through price mechanisms. Hence, water companies in England have been promoting to install water meters to households, in order to levy water charges on the basis of actual water consumptions. In fact, meter-charged households nearly always use less water than those who pay a fixed charge (Environment Agency, 2008a).

Nevertheless, in order to judge whether such scheme is truly beneficial to society, we need to answer two key questions. First, we must quantify exact magnitudes of water saving that might be achieved through water metering. Second, we ought to find whether such water saving is actually beneficial to society, by comparing costs and benefits of water metering.

Thus, this study is aimed at investigating the two questions raised above, and hence appraising social welfare of water metering, with East Anglia region as a case study. The outcome of study would provide useful information in promoting water metering in the future.

II Review of previous studies

1 Estimation of the demand effect of metering

In water industries, the fall in water consumption induced by installation of water meters is termed the "demand effect of metering" (DEM). Although appropriate estimation of the DEM is a prerequisite for the discussions of social welfare of metering, it remains a controversial area of study. For instance, Sharp (2006: 877) pointed out that water uses were often deeply embedded in culture, which might not be responsive to water pricing scheme. Nevertheless, this study will focus arguments on economics, especially econometric methodologies, regarding water metering.

The most primitive approach for estimating the DEM is to conduct a cross-sectional survey of households that include both non-metered and metered households, and simply compare mean water consumptions between them through the ordinary least square (OLS) regression (e.g. Gibbs, 1978). However, this approach may have shortcomings from the endogeneity problem: if there were unobserved heterogeneity between the two groups of households, estimates of the DEM would be biased.

An alternative method would be to construct a simultaneous equation model incorporating instrumental variables. For instance, Agthe et al. (1986) conducted a study in Arizona, USA, where fixed plus block fees were applied, and formed a three-equation system comprising a demand function for water and the other two describing the supply side of the water market, with the marginal price as endogenous variable. They demonstrated the OLS estimators of price elasticity were indeed biased on the basis of the Hausman test.

Another approach to overcome endogeneity is to employ panel data analysis, which can distinguish the effects of explanatory variables from unobserved household-specific effects. Nauges and Thomas (2000) applied panel data analysis to a study on privately operated water utilities in France, where water charges were decided through negotiations between local municipalities and private water companies. Hence, they argued, water prices might be affected by unobserved characteristics of the communities. They found there were indeed persistent omitted explanatory variables in each municipality.

The above studies suggest there could be a number of factors that may cause the endogeneity problem, depending on the water-pricing scheme under discussion. This study, on the other hand, is concerned with the demand effect of metering in England, where metering is largely optional and water prices are tightly regulated by an independent agency OFWAT. This calls, first of all, for an adequate theoretical framework that fits our situations (for example, we may well abstract from the supply-side considerations because of the regulations in water industries).

Thus, Chapter III begins by building microeconomic theoretical models that form the basis of subsequent econometric analyses. Chapter IV will then conduct cross-sectional econometric analyses including the simultaneous equation model, with a focus on the endogeneity problem of metering dummy variable. Chapter V will extend analyses to panel data to delineate the partial effect of metering dummy.

2 Social welfare of water metering

Social welfare is a complex subject that could be discussed from many perspectives. For instance, Chappell and Medd

(2008) argued: “current strategies for equitable [metered] charging … inadequately account for social and geographical differentiation in supply and demand”. This study, however, will concentrate on households’ incomes in discussing the social welfare of metering, since arguing every aspect of social and geographical dimensions is beyond our scope.

Cowan (2010) theoretically investigated tariff schemes that would bring socially efficient outcomes, when metering is optional. In that case, the scheme required that every meter installed would bring positive benefits both to the society and to the household. He examined cases where water companies may or may not have information on households’ types (i.e. their demand functions for water). He demonstrated that households with smaller elasticity of demand (i.e. those who would bring least benefit to society through water saving) would be more likely to opt for metering. This implies an adverse selection problem: those who are more expensive to serve (in terms of the cost-benefit ratio) would rather choose to have the service. He nonetheless concluded that, when water companies know households’ types, they could implement a tariff scheme that discourages “expensive” customers to install meters. On the other hand, such “separating equilibrium” did not exist when companies did not know households’ types.

Dresner and Ekins (2006) empirically investigated, with data from Anglian Water, how different (both the current and hypothetical) tariffs make households better-off or worse-off (in respect to tariff reduction). They found it possible to design progressive tariffs that would cause smaller percentage of lower income households to lose, relative to the current tariff. Their study, however, simplified the argument by assuming that metering was compulsory, and there was no DEM – water consumption was unchanged upon switching to metering.

This study will follow Cowan’s approach, because his model accurately incorporated the DEM and described the situation of optional metering. Specifically, we will study the case where water companies have households’ information, as it appears more promising than the asymmetric information case. We therefore focus on the information accessible to water companies: rateable value, which may act as a proximate indicator for incomes. Chapter III begins by discussing theoretical relationships between the rateable value and the water demand. Chapter VI then builds an empirical model on the basis of Cowan’s theory and econometric findings of Chapters IV and V.

III Microeconomic theory of water consumption and the demand effect of metering

This chapter explores theoretical backgrounds for consumers’ behaviours on water consumption and installation of water meters, by employing neoclassical consumer theory (Mas-colell et al., 1995; Varian, 1992). We aim to derive some propositions that are further tested using econometric methods in later chapters. We employ graphical analyses involving indifference curves and budget constraints. The corresponding mathematical analyses are discussed in **Appendix I**. The basic model of consumer behaviours on water consumption in Sections III-1-a to III-1-c is established on the basis of Kyle (2009). We then develop it in several directions in Sections III-1-d to III-1-g to derive three Propositions.

1 Graphical analyses

a. Households’ preference for water

We describe a households’ decision problem facing a two-good economy comprising water (x_1) and numeraire (“all other goods”, x_2). Regarding households’ preference for water, we impose two restrictions. First, we assume the preference is strictly convex until x_1 reaches a satiation point (discussed below), implying that the household has a diminishing marginal rate of substitution (MRS) for water. This is a plausible assumption, because households would demand water for various reasons, which can be aligned from the most indispensable (or valuable) to the least, i.e. in the descending order of the MRS[1].

Second, we assume the demand for water has a satiation point c, and water consumption beyond this point adds no extra utility to household, implying that water is a ‘stable good’ in such a situation. Although this assumption implies that households are indifferent between consuming c and c' where $c < c'$, we further impose a restriction that households

[1] To begin with, we ought to drink about two litres of water in order to survive, and there is no substitute for water in this regard. Next come other basic human needs such as washing hands and bodies to keep sufficient personal hygiene. After those needs are satisfied, we then also appreciate using water for flushing toilet and washing clothes and dishes. Finally we may also enjoy so-called ‘discretionary uses’ such as watering gardens and feeding swimming pools, which are not essential but may give us some pleasures.

would choose to consume c rather than c' when the budget constraint allows them to consume either one of them[2].

Consequently, an indifference curve of a household on the two-good plane could be depicted as **Fig.1**. The curve is strictly convex where $x_1<c$, and horizontal where $x_1 \geq c$. According to the monotonicity principle of consumer demands, it is apparent that households attain higher utilities when they move on to the northeast direction on the plane.

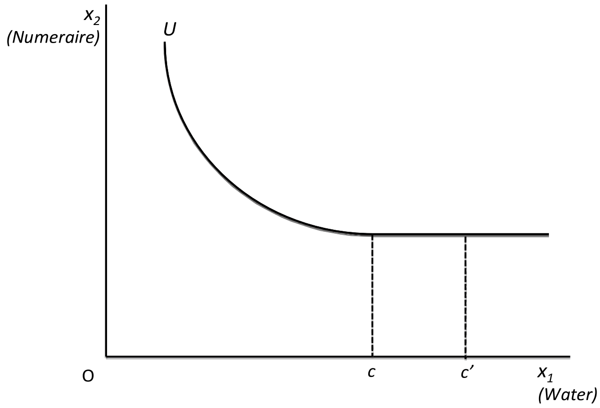

Fig. 1 Indifference curve of a household facing the two-good economy

b. Budget constraints

In the two-good economy we discuss, a household (with an income m) faces different budget constraints depending on the water charging schemes. First, when water is not metered, households pay a flat charge for water f that is levied proportional to the rateable value (RV) of their properties[3], regardless of the amount of water they consume. Hence we have:

$$f = k \times RV \tag{1}$$

where f is a flat charge for water (and hence total expenditure on water), k is a positive constant and RV is a rateable value.

Thus, we have a **flat-charge budget constraint** $\boldsymbol{B_f}$:

$$f + x_2 \leq m$$

or $$x_2 \leq m - f \tag{2}$$

where we normalise the price of numeraire as one.

Hence the budget constraint curve is a horizontal line intercepting the x_2 axis at $(m\text{–}f)$ (**Fig.2**).

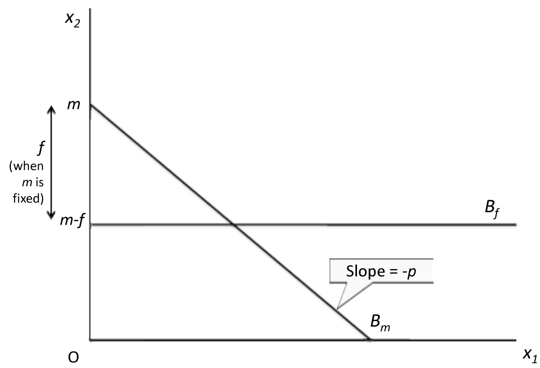

Fig.2 Budget constraints of a household facing the two-good economy

2 This assumption would be plausible because, in spite of the 'stable-good' assumption discussed above, consuming (or wasting) water in excess of the satiation point might actually be utility decreasing in some senses. For instance, wasting water (letting tap water running without any uses) may give us a sense of guilt; and hearing a noise of running water in a sink whilst sleeping is hardly pleasurable. However, we will not model such possibility as it violates the axiom of monotonicity in the consumer theory and hence complicates the analysis.

3 Exactly speaking, both the flat and metered charges include "standing charge" that is unrelated to the RV or water consumptions. However, we abstract from this fact for simplicity until Chapter VI.

Second, when water is charged with metering, households pay a charge proportional to the amount of water consumed. So we set the price of water (when meter-charged) at p. Then we have a **meter-charge budget constraint B_m**:

$$px_1 + x_2 \leq m$$

or $$x_2 \leq m - px_1 \tag{3}$$

Thus, the budget constraint line is a downward-sloping straight line with a slope $-p$ and an x_2 intercept m (**Fig.2**). It should be noted that, when a household opts for metering, their budget constraint line shifts from B_f to B_m (**Fig.2**), *ceteris paribus*. Thus, by holding m constant, the x_2 intercept will shift upwards by f.

c. Optimal consumption of water

Having defined households' preferences and budget constraints, we are now able to explore the optimal consumption bundle X: (x_1, x_2) for a utility-maximising household. This is given at a tangency point of the indifference curve and the budget constraint, where the maximum utility is attained subject to the affordable budget set discussed in Section III-1-b.

When a household is flat-charged, they face a horizontal budget constraint B_f: $x_2=m-f$, and therefore the tangency is not a singleton but a convex set (a straight line segment): $S=\{(x_1, x_2): x_1 \geq c, x_2=m-f\}$ (**Fig.3**). Nevertheless, according to the "no wasting of water" assumption discussed in Section III-1-a, we may well pin down the **flat-charge optimal bundle** at X_f**:** (x_1^f, x_2^f) = $(c, m-f)$. By contrast, when a household is meter-charged, the optimal bundle shifts to a tangency point of B_m and the indifference curve, which is X_m**:** (x_1^m, x_2^m) (**Fig.3**). (We solve this **meter-charge optimal bundle X_m** mathematically in **Appendix I**.)

Next, we further model that a utility-maximising household decides to switch from flat charge to water metering or otherwise, by comparing the maximum utility (i.e. indirect utility) subject to the flat-charge constraint (U_f), and that subject to the meter-charge constraint (U_m), given the household's m, f and c. Hence we set the following **switching criteria**:

A household will:
- **Case (1)**: opt for metering if $U_m > U_f$
- **Case (2)**: be indifferent between the two options if $U_m = U_f$ and
- **Case (3)**: opt out if $U_m < U_f$.

Fig.3 shows the Case (2). Nevertheless, depending on the relative magnitudes of m, f and c, Cases (1) and (3) are also possible (**Fig.4**).

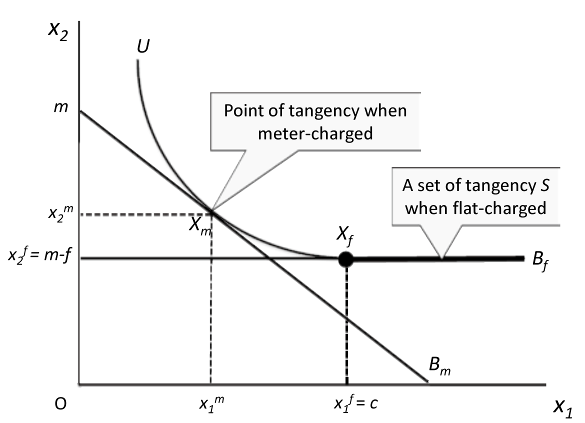

Fig.3 Optimal bundles for a household facing the two-good economy

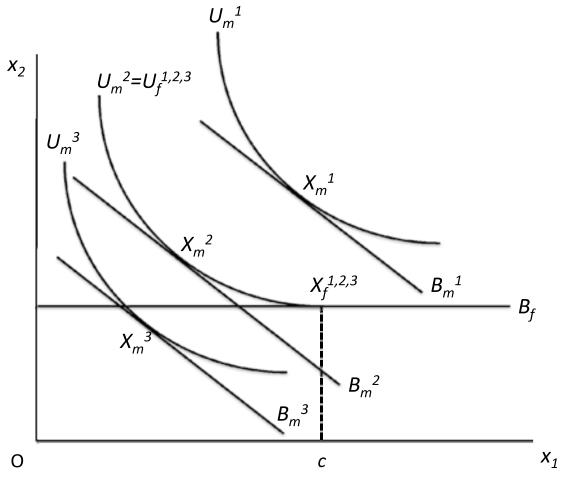

Fig.4 Schematic diagram for the metering decisions
Note: superscripts 1, 2, 3 correspond to cases (1), (2), (3) in text.

d. Water consumption and the metering decision

By exploiting the theoretical framework we have discussed, we next investigate some of the important relationships concerning household water consumptions and their decisions on water metering options. We begin by examining the effect of household's water consumption on the metering decision. Specifically, we hypothesise here that the amount of water consumption *before* switching to metering would have an influence on the subsequent metering decisions. Since a household is flat-charged before switching[4], here we should use the "flat-charge optimal bundle" $\boldsymbol{X_f}$ derived in Section III-1-c. We have derived that the optimal water consumption when flat-charged (x_1^f) would equal to the satiation point, c. Thus, we are required to demonstrate a relationship between household's c and the metering decision, by holding household's m and f constant.

The relationship is depicted in **Fig.5**. Since we hold m and f constant here, the budget constraints $\boldsymbol{B_f}$ and $\boldsymbol{B_m}$ are also fixed. The metering decision therefore depends solely on the position of c, which reflects households' different preferences on water[5]. Hence **Fig.5** shows three cases (1), (2) and (3) with different c whilst fixing $\boldsymbol{B_f}$ and $\boldsymbol{B_m}$. According to the switching criteria in Section III-1-c, we could therefore conclude that the household will opt for water metering in Case (1); be indifferent in Case (2); and opt out in Case (3). That is, the smaller the c, the more likely the household switches to metering. Hence we established a proposition:

> **Proposition 1**: The *less* water the household consumes when flat-charged, the more likely they opt for water metering, *ceteris paribus*. In other words, there is a negative relationship between the water consumption before switching and the propensity to switch to metering.

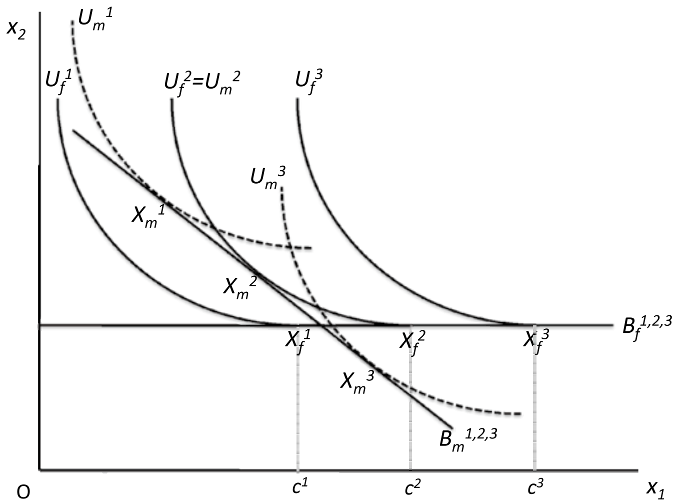

Fig.5 Relationship between pre-metering water consumption and the metering decisions

e. Rateable values and the metering decision

We next hypothesise that the rateable value of household has an effect on the metering decisions. Since a flat-charge for water f is paid proportional to the rateable value, we hereafter treat f as a surrogate indicator for the rateable value. Although we naturally expect that there is a positive relationship between household's income m and f, we will hold m constant for now whilst allowing f to vary[6], in order to keep graphical depiction simple. We also assume that c is constant[7]

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[4] We are considering here only the option to switch from flat-charge to meter-charge, although the reverse decision is also allowed in part under the current scheme.

[5] The satiation point c would differ across households for a number of reasons, such as occupancy and the number/size of water-consuming appliances and gardens they possess.

[6] In other words, we are discussing here about the relative magnitude of f to a given m. As long as we maintain that m is given, our conclusion to this section will hold for any given level of m. This is because increasing (decreasing) m would simply shift up (down) both $\boldsymbol{B_m}$ and $\boldsymbol{B_f}$ without changing their relative positions, whilst indifference curves are assumed to be quasi-linear with respect to the numeraire (**Fig.6**). This argument is confirmed mathematically in Appendix I, where we demonstrate that the propensity to opt for metering d^* is independent of m (equation 61).

[7] This assumption appears to contradict our earlier arguments in Section III-1-d, and therefore requires some explanations. More precisely, we assume here: c does not change in response to m and f, once we control for the occupancy and the number/size of appliances etc. the household would possess. [As a concrete example, think of university accommodation. Each room is flat-charged for water, accommodates the same number of persons, and equipped with exactly the same appliances. Yet both well-offs and worse-offs (due to parents' incomes) may live there. Our assumption is therefore water consumptions are not systematically different across such rooms.] In other words, we claim that people's *intrinsic* desires for water would remain the same no matter how rich or poor they were. We will test this econometrically in Section IV-2-a-(2).

in this and the subsequent sections.

The relationship is depicted in **Fig.6**. Since we hold *m* constant, the budget constraint $\boldsymbol{B_m}$ is fixed, whilst $\boldsymbol{B_f}$ shifts up and down in proportion to *f*. Since x_2 intercept of $\boldsymbol{B_f}$ is $(m–f)$, $\boldsymbol{B_f}$ is shifted *down* when *f* gets larger. **Fig.6** presents three cases with different *f*. Again, judging from our switching criteria, we could conclude that the household will opt for water metering in Case (1); be indifferent in Case (2); and opt out in Case (3). That is, the larger the *f*, the more likely the household opts for metering. Hence we established a proposition:

Proposition 2: The larger the rateable value of a household, the more likely they opt for water metering, *ceteris paribus*. In other words, there is a positive relationship between the rateable value and the propensity to switch to metering.

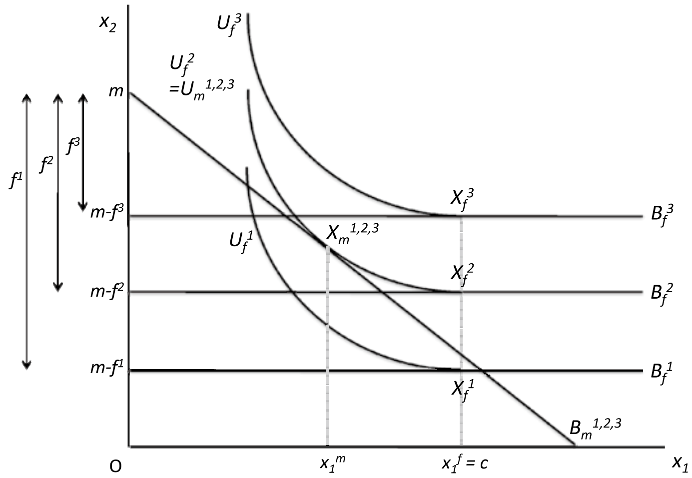

Fig.6 Relationship between rateable values and the metering decisions

f. Existence of the demand effect of metering

The demand effect of metering (DEM) is defined as a reduction in water demands when a household switches to water metering[8]. In **Fig.6**, it is apparent that x_1^m is always located to the left of x_1^f when a household switches to metering, holding *c* (i.e. occupancies etc.) constant. Hence we conclude there exists a positive DEM (in the absolute value term). This is confirmed mathematically in Appendix I-2.

g. Rateable value and the demand effect of metering

We now hypothesise that there is an inverse relationship between the rateable value (hence *f*) and the DEM[9]. That is, the smaller the rateable value, the larger the DEM. The explanation goes as follows. We first assume a positive relationship between *m* and *f* (that is, the wealthier the household, the higher the RV of their properties). We then assume different marginal rates of substitution (MRS) for water among households. Specifically, we assume that the wealthier the households, the higher their MRS for water would be. That is, the rich are more willing to pay (in terms of the numeraire) for consuming additional amount of water below the satiation point[10].

This assumption leads to progressively steeper indifference curves as we move up the two-good plane, i.e. as the household gets wealthier (**Fig.7**). This in turn suggests that the rich would be prepared to pay for ampler water consumption, and hence save less water upon switching to metering, relative to the poor. This of course implies that the rich tends to have smaller DEM[11].

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[8] It should be noted that we define the DEM in the absolute-value term throughout this study. Hence, the DEM is always expressed as a positive value, although the change in water consumption upon switching to metering is likely to be negative (i.e. the demand is reduced).

[9] This section focuses on households that do switch to metering. In other words, we abstract from the effect of the RV on metering decisions (Proposition 2).

[10] Such a type of utility function has been suggested by Cowan (2010: 804), who modelled that "a household with a higher type has a higher marginal utility of consumption at all quantities below its satiation level". [However, "higher types" here not necessarily imply wealthier households.] Likewise Arbués et al. (2003: 85) reported that several works had estimated different demand functions for different income levels.

[11] This conclusion leads us to another claim that: the *meter-charged* water consumption (x_1^m) is increasing in income, *ceteris paribus*. This is obvious in **Fig.7**, and will be tested empirically in Section IV-2-a-(2).

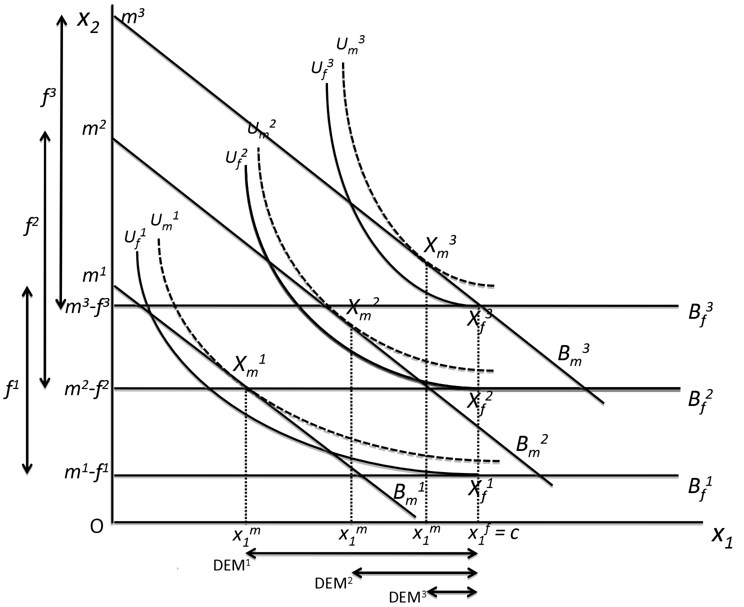

Fig.7 Relationship between rateable values and the DEM
Note: Cases (1), (2) and (3) represent low, middle, and high-income households, respectively.

We could now summarise the arguments as follows:
(a) Households with higher *f* tend to be wealthier. [By assumption]
(b) The rich tends to save less water upon switching to metering. [Due to their higher MRS]
(c) Hence, they would have smaller DEM.
Thus, we have derived a proposition:

Proposition 3: The larger the rateable value of a household, the smaller the demand effect of metering (DEM), *ceteris paribus,* given the household do switch to metering. In other words, there is a negative relationship between the rateable value and the DEM.

2 Summary

This chapter has derived three fundamental propositions on households' water consumption on the basis of microeconomic consumer theory. These will be tested extensively with econometric methods in subsequent chapters.

IV Econometric analyses of water consumption with cross-sectional data of households

Having established theoretical frameworks for water consumptions and metering decisions in Chapter III, we now proceed to challenge those theories with econometric analyses. This chapter will use a cross-sectional survey on water consumption to estimate the demand effect of metering. Throughout Chapters IV and V, references are made extensively to Kyle (2009) regarding the datasets and several econometric techniques. In particular, we owe most of the materials to her study in discussing the coherency condition in Section IV-2-d-(1). On the other hand, we extend her analyses in Sections IV-2-a-(2), IV-2-b and IV-2-d-(3), and substantially revise the modelling descriptions in Section V-1.

1 Background and descriptions of data

a. Background of the data

The data used in Chapters IV and V were obtained from the Anglian Water Services Ltd., which is the monopoly supplier of water covering most of the East Anglia region. From 1990 to 2001, the company conducted a survey called "Survey of domestic water consumption", in order to investigate determinants of household water consumption (Kyle, 2009). The sample consists of 1,873 non-metered and 903 metered households, with a total of 2,776[12]. Those households were fitted with a supplementary meter, which recorded water consumption data at every fifteen minutes. In addition, they were interviewed to collect additional information on their socio-economic characteristics.

The data set used in this chapter was observed on the above sample, in a one-year period between 1999 and 2000. The sample did not contain households that switched from non-metered to metered status in the course of the observation period. The original data of water consumption was summed up to obtain an annual consumption of water. Thus, the procedures imply that the water consumption data were collected *after* the households had made their decisions to opt for metering or otherwise. As we discuss later, this point has an important ramification in discussing an effect of water consumption on the metering decision.

b. Definitions and descriptions of the data

Definitions of the variables used in this chapter are presented in **Table 1**, and their descriptive statistics in **Table 2**. **Table 2** summarises the statistics of the whole sample as well as those for metered and non-metered households only[13].

Table 1 Definitions of the variables

Variable	Definitions and descriptions
Water consumption	Household's annual water consumption in 1999-2000 (litres)
Meter	Water-metering dummy: 1 if household metered; 0 if not
Occupancy	Number of persons living in a household
Dummy variables concerning water-consuming appliances and activities	
Washing machine	1 if owned; 0 if not
Dishwasher	1 if owned; 0 if not
Dual-flush toilet	1 if owned; 0 if not (Dual-flush toilet is a device intended to reduce water consumption in flushing.)
Power shower	1 if owned; 0 if not
Wash vehicle	1 if washes vehicle; 0 if not
Hose	1 if owned; 0 if not (*Hose* means summer hoses normally used for watering gardens)
Sprinkler	1 if owned; 0 if not
Water softener	1 if owned; 0 if not
Dummy variables indicating households' income status	
ACORN A	1 if top occupational class (wealthy achievers); 0 if not
ACORN B	1 if second occupational class (urban prosperity); 0 if not
ACORN C	1 if third occupational class (comfortably off); 0 if not
ACORN D	1 if fourth occupational class (moderate means); 0 if not
ACORN E	1 if fifth occupational class (hard-pressed); 0 if not
Rateable value (RV)	Rateable value of household when a house was built
Year-built	The year household was built (a.d.) minus 1900

Note: *ACORN* stands for "A Classification of Residential Neighbourhoods" (see text, Section IV-1-b-(3)).

Table 2 Descriptive statistics of the cross-sectional data

	Whole sample					Metered households					Non-metered households				
Variable	Obs	Mean	S.D.	Min	Max	Obs	Mean	S.D.	Min	Max	Obs	Mean	S.D.	Min	Max
Water consumption															
annual (L)	2776	85596	61086	525	417981	903	55423	42278	570	231529	1873	100144	63398	525	417981
in natural log	2776	11.023	0.962	6.263	12.943	903	10.563	0.973	6.346	12.352	1873	11.244	0.874	6.263	12.943
*per-day (L)**	2776	234.511	167.359			903	151.843	115.830			1873	274.366	173.694		
*per-capita-day (L)***	2776	90.291	125.463			903	77.995	114.230			1873	94.257	128.056		
Meter	2776	0.325	0.469	0	1										
Occupancy	2776	2.597	1.334	1	9	903	1.947	1.014	1	6	1873	2.911	1.356	1	9
Washing machine	2776	0.949	0.220	0	1	903	0.908	0.289	0	1	1873	0.968	0.175	0	1
Dishwasher	2776	0.254	0.435	0	1	903	0.262	0.440	0	1	1873	0.249	0.433	0	1
Dual-flush toilet	2776	0.141	0.348	0	1	903	0.120	0.325	0	1	1873	0.151	0.358	0	1
Power shower	2776	0.220	0.414	0	1	903	0.255	0.436	0	1	1873	0.203	0.402	0	1
Wash vehicle	2776	0.173	0.378	0	1	903	0.116	0.321	0	1	1873	0.200	0.400	0	1
Hose	2776	0.564	0.496	0	1	903	0.503	0.500	0	1	1873	0.593	0.491	0	1
Sprinkler	2776	0.055	0.228	0	1	903	0.061	0.239	0	1	1873	0.052	0.222	0	1
Water softener	2776	0.017	0.130	0	1	903	0.022	0.147	0	1	1873	0.015	0.121	0	1
ACORN A	2776	0.216	0.411	0	1	903	0.268	0.443	0	1	1873	0.191	0.393	0	1
ACORN B	2776	0.189	0.392	0	1	903	0.161	0.367	0	1	1873	0.203	0.403	0	1
ACORN C	2776	0.139	0.346	0	1	903	0.121	0.326	0	1	1873	0.148	0.355	0	1
ACORN D	2776	0.327	0.469	0	1	903	0.340	0.474	0	1	1873	0.321	0.467	0	1
ACORN E	2776	0.128	0.334	0	1	903	0.111	0.314	0	1	1873	0.137	0.344	0	1
Rateable value (RV)	2776	216.966	90.250	46	980	903	249.498	105.405	68	662	1873	201.282	77.227	46	980
Year-built (minus 1900)	2776	59.139	21.480	5	95	903	62.829	18.477	5	95	1873	57.360	22.577	5	95

Note: Obs: the number of observations; S.D.: standard deviation
* Per-day water consumption = annual consumption / 365
** Per-capita-day consumption = per-day consumption / occupancy.

12 Households were initially sampled on the basis of a stratified random sampling approach, although actual inclusion in the survey was conditional on their approvals.

13 All the statistical calculations of this study are performed with the statistical software Stata 11 (StataCorp LP).

Further descriptions of some variables are provided below.

(1) Water consumption

The procedures to generate water consumption data have been described in Section IV-1-a. **Table 2** shows that there is a big difference in mean water consumptions between the metered (55,423) and the non-metered (100,144). Nevertheless, we should be careful not to interpret this as the demand effect of metering, as we discuss in Section IV-2-c.

A histogram of *water consumption* (**Fig.8**) shows that the consumption is roughly uni-modal but heavily skewed to the right, with a long tail at large consumption. By contrast, a histogram of natural log of *water consumption* (**Fig.9**) is skewed to the left, but it appears closer to symmetry than **Fig.8**. Hence we choose to use the natural log in the analyses. The use of natural log in the dependent variable also gives a convenience that OLS estimators of parameters (multiplied by 100) represent semi-elasticity, that is, a percentage change in the dependent variable in response to a unit change in explanatory variables.

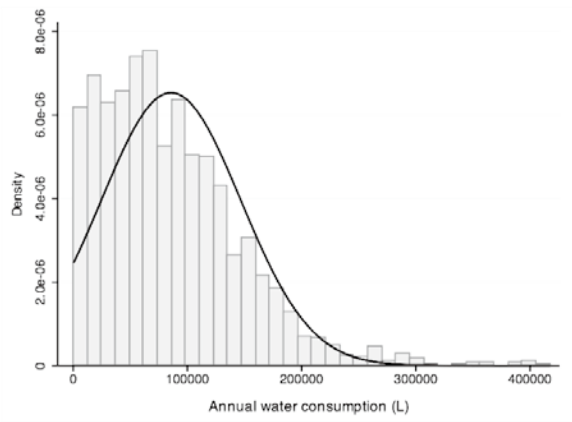

Fig.8 Histogram of annual water consumption (in litres)

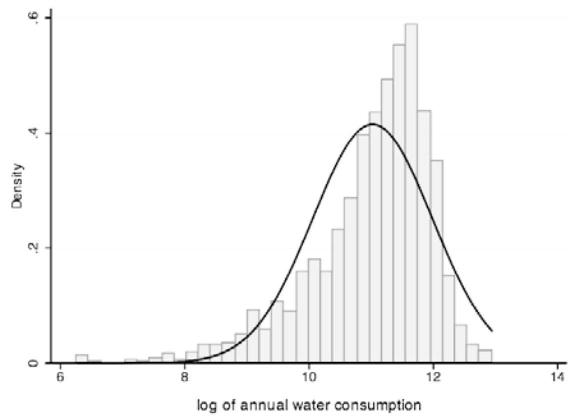

Fig.9 Histogram of natural log of annual water consumption

(2) Occupancy

We naturally expect that larger occupancy of household would lead to larger water consumption. Nevertheless, such a relationship may not be linear. Hence, a scatter plot is drawn in **Fig.10** with the Lowess smoother, which provides locally weighted scatter-plot smoothing.

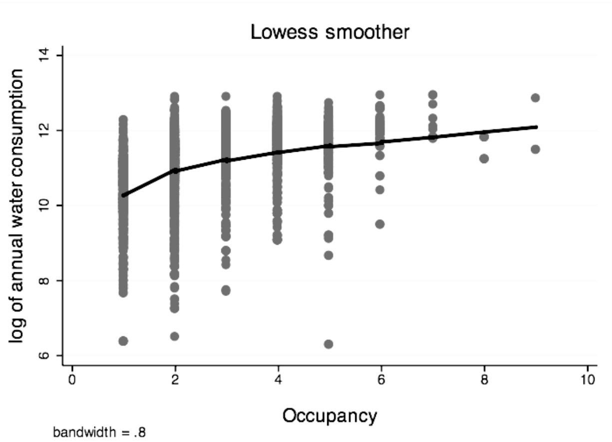

Fig.10 Log of annual water consumption against occupancy with the Lowess smoother

A shape of the Lowess smoother implies that there is a concave relationship between the occupancy and the water consumption. Hence we shall include a square of occupancy in the explanatory variables to accommodate such concavity.

(3) Dummy variables

We include a dummy on water metering (*meter*) as well as those regarding water-consuming appliances and activities of households, and those indicating their social status (*ACORN* dummies) (**Table 1**). In **Table 2**, the means of the dummy variables indicate the frequency of household belonging to the "yes" category. For instance, 32.5% of the sample had a water meter installed, 94.9% had a washing machine, and so on.

ACORN (which stands for "A Classification of Residential Neighbourhoods") is a geo-demographic classification system for small areas in the UK, due to CACI Ltd.[14]. There were five ACORN groups in the region, ranging from ACORN A (the highest socio-economic group) to ACORN E (the lowest). (The labels that define each group are provided in parentheses in **Table 1**.) These dummies are expected to act as surrogate indicators for household incomes, which is not available in this data set.

(4) Rateable value

The rateable value (RV) of a property is closely related to its market value, and is determined by a local government at the time a house is built. The RV is what determines a flat charge payable if a household is non-metered.

In Chapter III, we have theorised that the higher the RV, the more likely the household would opt for metering. This is provisionally confirmed in **Table 2**, which shows the mean RV of the metered (249) is larger than that of the non-metered (201). This is formally analysed in Section IV-2-b.

(5) Year built

This variable indicates the year in which the property was built. Since it is given as interval data, we shall use the mid-point of each interval to represent the year built[15]. We then subtract 1900 so that the variable has a sensible range.

The reason why we include this variable for the analyses is that it has an important effect on the probability of metering: properties built in later years have higher probabilities of being metered, simply because installations of meters to new properties have become routine in recent years. This is confirmed in **Table 3**, which shows generally higher proportions of metered households for newer properties.

Table 3 Percentage of metered households for each "*year-built*"

Year-built	*n*	% metered
1905	120	7.5
1915	43	20.9
1925	93	26.9
1935	369	27.4
1945	174	30.5
1955	390	35.6
1965	513	37.8
1975	643	30.8
1985	411	41.8
1995	20	15.0
Total	2776	32.5

2 Econometric models with a single cross-sectional data

a. Model 1: the OLS model on water consumption

(1) The OLS analysis on water consumption

Since our final objective of this chapter is to quantify the demand effect of metering, we first build an **ordinary least square (OLS) model** with (natural log of) annual water consumption as the dependent variable, and other variables described in Section IV-1 (including the metering dummy) as explanatory variables.

Specifically, we assume a model:

$$y_i = \gamma d_i + \beta' x_i + u_i \qquad i = 1, \ldots, n \tag{4}$$

[14] For more information, see: http://www.caci.co.uk/

[15] Properties built before 1910 were assigned a year of 1905.

$u_i \sim N(0, \sigma^2)$

where: y_i is the natural logarithm of annual water consumption by a household i,

d_i is the metering dummy: d_i=1 if metered; 0 otherwise.

x_i is a vector of other explanatory variables describing household characteristics,

γ is a parameter representing a proportionate effect of metering on consumption,

β is a vector of parameters, the first of which is an intercept.

The results of the OLS estimation are reported in **Table 4**. In **Model 1a,** x_i contains all the available variables, whereas **Model 1b** excludes *RV* and *year-built*. These two variables will have to be excluded when we construct a simultaneous equation model later. Hence we will focus on **Model 1b**, which would be compatible with later models.

R^2 for Model 1b (0.28) is disappointing but not too low, given this is a cross-sectional dataset involving a lot of "noise". The Breusch-Pagan test for heteroscedasticity is conducted for both models, where:

H_0: constant variance

and the test statistic follows $\chi^2(k-1)$, where k−1 is the number of explanatory variables excluding the constant.

According to the reported test statistic (**Table 4**), we reject H_0 at the 1% level and hence conclude there is strong evidence of heteroscedasticity, whose presence implies that OLS standard errors are invalid. Therefore, we alternatively use heteroscedasticity-robust (White-corrected) standard errors, which have been reported in **Table 4**.

Table 4 Estimated log-linear OLS models for water consumption (1)

	Model 1a			Model 1b		
Variables	Coefficients	Std. errors		Coefficients	Std. errors	
Constant	9.456997	0.1207642	**	9.568039	0.110838	**
Meter	-0.5017501	0.0405846	**	-0.4293487	0.0380484	**
Occupancy	0.4205556	0.0434185	**	0.4515597	0.0438446	**
Occupancy-squared	-0.0350478	0.0060113	**	-0.0386853	0.0060785	**
Washing machine	0.4656842	0.0912308	**	0.4893487	0.0918606	**
Dishwasher	0.0330314	0.039196		0.1148438	0.0365226	**
Dual-flush toilet	0.0316573	0.0420191		0.0305476	0.0423491	
Power shower	0.0949787	0.0365898	**	0.1216313	0.0365586	**
Wash vehicle	0.0983317	0.0407352	*	0.1104261	0.0411423	**
Hose	0.1318097	0.0353448	**	0.156608	0.035976	**
Sprinkler	0.0391326	0.0542091		0.0719033	0.0558938	
Water softener	0.2128433	0.096525	*	0.3019385	0.0967389	**
ACORN A	0.1290317	0.0599784	*	0.2255011	0.0582402	**
ACORN B	0.0359772	0.0591985		0.0825881	0.0569571	
ACORN C	0.0637679	0.064731		0.080075	0.0640318	
ACORN D	0.0837083	0.0546964		0.1058565	0.0551216	
ACORN E (base)	0	0		0	0	
Rateable value (RV)	0.0014108	0.0002298	**			
Year-built (minus 1900)	-0.0002452	0.0008833				
Sample size	2776			2776		
R^2	0.2900			0.2789		
Breusch-Pagan test	122.76	(df=17; p=0.0000)		101.52	(df=15; p=0.0000)	

Dependent variable: ln (*water consumption*)
Heteroscadasticity-robust standard errors are shown.
* Significant (p<0.05); ** Strongly significant (p<0.01)

Next, the coefficients of Model 1b could be interpreted as follows.

- The coefficient on *meter* implies that metered households would consume 42.9% less water than non-metered ones on average, *ceteris paribus*. Nonetheless, we should not interpret this as the DEM, for reasons explained later.
- The positive sign of the *occupancy* coefficient together with the negative sign of the *occupancy-squared* coefficient imply a concave relationship between occupancy and the dependent variable. This may make sense because, as the occupancy increases, the members of a household tend to share some water-consuming facilities such as dishwashers and washing machines. Such sharing may reduce per-capita water consumption as occupancy increases, and

hence result in the concave relationship observed.

- Dummy variables on household equipments (excluding *dual-flush toilet* and *sprinkler*) are all positive and significant at the 1% level. This implies that their uses have strong positive effects on water consumption. In particular, a strong effect of *washing machine* (48.9%) should be noticed. This could be expected because, when a household does not possess a washing machine, they may tend to get laundry services outside home. On the other hand, a positive and insignificant coefficient on *dual-flush toilet* is disappointing, because it is intended to *save* water consumption in flushing toilet.
- The *ACORN* variables (excluding *ACORN A*) are individually insignificant. Nonetheless, the F-test[16] implies that *ACORN* variables are *jointly* significant at the 5% level. Hence we choose to maintain them in the independent variable. Further analyses on *ACORN* variables are presented below in Section IV-2-a-(2).

(2) Further analyses on relationships between income and water consumption

This section challenges the relationship between income and water consumption proposed in Chapter III, by extending the proceeding OLS analyses. Firstly, throughout Sections III-1-e to III-1-g, we hypothesised that the satiation point, c ($=x_1^f$), would be independent of incomes, once we control for occupancy and household appliances etc. (**Figs.6 and 7**). Now we shall test this hypothesis, by assuming that: *ACORN* variables act as proxy indicators for household incomes; and water consumptions of non-metered households equal the satiation point. By accepting these assumptions, then, the hypothesis can be interpreted as: *ACORN* variables are jointly *in*significant in determining water consumptions of *non-metered* households, given occupancy and appliance dummies are included in the explanatory variables.

Thus, after picking only non-metered households from the whole sample, we conduct the F-test on Model 1b (but with *meter* excluded due to multicollinearity):

H_0: $\beta_{ACORN\ A} = \beta_{ACORN\ B} = \beta_{ACORN\ C} = \beta_{ACORN\ D} = 0$

Number of restrictions=4 df =1858 R^2_R=0.1904 R^2_U=0.1928.

F=1.3811 < 2.37=$F_{0.05,4,\infty}$. Hence we *fail to* reject H_0 at the 5% level.

Hence we conclude that *ACORN* variables are jointly *in*significant in determining water consumption of non-metered households. In addition, it is shown that all the *ACORN* variables are individually *in*significant at the 5% level when only non-metered households are estimated (**Model 1c**, **Table 5**). All these results would suggest that water consumptions of non-metered households (and hence their satiation points) would be independent of income levels, *ceteris paribus*.

Secondly, our discussions in Section III-1-g also suggested that water consumption of metered households, x_1^m, would be increasing in income (**Fig.7**), holding occupancy and appliances etc. constant. This can be tested using **Model 1d** (**Table 5**), where only metered households are estimated.

Here the coefficients on *ACORN* dummies indicate the percentage-point difference in water consumption between *ACORN A* (or *B, C, D*) and *ACORN E* (base), which is the least well-off group. Therefore, if the above hypothesis is true, these coefficients should be significantly positive (because the well-offs should have higher water consumption relative to the worse-offs when meter-charged). **Table 5** indicates that coefficients on *ACORN A* and *D* are indeed significantly positive at the 1% level, and the magnitudes of these coefficients are larger than those in Model 1b (**Table 4**) or Model 1c. F-test[17] also gives evidence that the *ACORN* variables are *jointly* significant at the 5% level in determining water consumption of *metered* households.

In summary, these results on Models 1c and 1d together suggest that the theoretic model we built in Section III-1-g (i.e. constant x_1^f and increasing x_1^m with respect to income, *ceteris paribus*) would be plausible, although the evidence is not decisive (as the variables *ACORN B* and *C* remain insignificant in Model 1d).

---

[16] We conduct a F-test on Model 1b as the unrestricted model:

H_0: $\beta_{ACORN\ A} = \beta_{ACORN\ B} = \beta_{ACORN\ C} = \beta_{ACORN\ D} = 0$

Number of restrictions=4 Degree of freedom=2760 R^2_R=0.2741 R^2_U=0.2789.
Hence F=4.5930 > 2.37=$F_{0.05,4,\infty}$. Hence we reject H_0 at the 5% level.

[17] We conduct the F-test for metered households only:

H_0: $\beta_{ACORN\ A} = \beta_{ACORN\ B} = \beta_{ACORN\ C} = \beta_{ACORN\ D} = 0$

Number of restrictions=4 df=888 R^2_R=0.1843 R^2_U=0.2065.
Hence F=6.2110 > 2.37=$F_{0.05,4,\infty}$. Hence we reject H_0 at the 5% level.

Table 5 Estimated log-linear OLS models for water consumption (2)

	Model 1c (non-metered only)			**Model 1d (metered only)**		
Variables	Coefficients	Std. errors		Coefficients	Std. errors	
Constant	9.639336	0.1415714	**	8.894288	0.1795075	**
Meter	(omitted)			(omitted)		
Occupancy	0.4652651	0.0504361	**	0.5673133	0.1278768	**
Occupancy-squared	-0.0386122	0.0066199	**	-0.0699946	0.0250039	**
Washing machine	0.4380143	0.1181706	**	0.4993862	0.1388852	**
Dishwasher	0.1260598	0.0426819	**	0.0687615	0.0704544	
Dual-flush toilet	0.0196069	0.0459181		0.0405792	0.094333	
Power shower	0.0835544	0.0426049	*	0.2097228	0.0676766	**
Wash vehicle	0.0911123	0.0459246	*	0.1901445	0.0896368	*
Hose	0.1619219	0.0434059	**	0.1617878	0.0615619	**
Sprinkler	0.0127534	0.059067		0.1656405	0.1098326	
Water softener	0.3830476	0.1170115	**	0.1755148	0.1588119	
ACORN A	0.1231678	0.0679741		0.4202365	0.1130535	**
ACORN B	0.0822888	0.0642613		0.0809853	0.1193665	
ACORN C	0.0476031	0.0732993		0.1652005	0.1261905	
ACORN D	0.0165228	0.0655141		0.3183032	0.1045006	**
ACORN E (base)	0	0		0	0	
Sample size	1873			903		
R^2	0.1928			0.2065		

Dependent variable: ln (*water consumption*)
Heteroscadasticity-robust standard errors are shown.
* Significant (p<0.05); ** Strongly significant (p<0.01)

b. Model 2: the probit model on metering decisions

In Chapter III, we have theorised that water consumption and RV would have an effect on the metering decision. Hence we next explore an econometric model with the water-metering dummy as dependent variable, and other variables as explanatory ones. Since the dependent variable is a binary one, we should employ qualitative response (QR) models that have been developed for dealing with such cases. Specifically, we shall use the **probit model**, which is one of QR models.

Hence, we assume a model:

$$d_i^* = \alpha' z_i + v_i \qquad i = 1, \ldots, n \tag{5}$$

$$v_i \sim \mathrm{N}(0, 1)$$

$$d_i = 1 \quad \text{(opt for metering)} \quad \text{if } d_i^* > 0;$$

$$d_i = 0 \quad \text{(opt out)} \quad \text{if } d_i^* \leq 0$$

where: d_i^* is a latent propensity to opt for water metering,
z_i is a vector of explanatory variables describing household characteristics,
α is a vector of parameters, the first of which is an intercept.

The results of probit estimation are reported in **Table 6**. In **Model 2a,** z_i contains all the available variables, whereas **Model 2b** excludes log of *water consumption*. First, Model 2a shows that *water consumption* has strong negative effect on meter installations. That is, the more water the household consumes, the less likely they would have a water meter. This appears to endorse our earlier Proposition 1 (Section III-1-d). Nevertheless, that proposition was concerned with the water consumption *before* the metering decision is made, whereas this cross-sectional data is about the water consumption *after* the decision is made. Hence exact analogy cannot be drawn between Proposition 1 and the current observation. Besides, we will have to exclude *water consumption* from this equation anyway when we later construct a simultaneous equation model, in order to meet the requirement of coherency. For these reasons, we will exclude *water consumption* from this model, and hence focus on **Model 2b**, which would be compatible with later models.

Table 6 Estimated probit models for the metering decisions

	Model 2a			Model 2b		
Variables	Coefficients	Std. errors		Coefficients	Std. errors	
Constant	3.678862	0.3704942	**	0.0082197	0.1712895	
Rateable value (RV)	0.005625	0.0005549	**	0.0051566	0.0004946	**
Year-built (minus 1900)	0.0059733	0.0015366	**	0.0059049	0.001476	**
Occupancy	-0.6523707	0.0851486	**	-0.8687662	0.0743547	**
Occupancy-squared	0.0502258	0.0132878	**	0.0710574	0.0110429	**
Washing machine	-0.1143826	0.1292469		-0.290333	0.1209672	*
Dishwasher	0.0129428	0.0738315		0.0089908	0.0727995	
Dual-flush toilet	-0.0873819	0.0819958		-0.1128291	0.0800711	
Power shower	0.1875031	0.0681181	**	0.1515212	0.0664262	*
Wash vehicle	-0.2942412	0.089252	**	-0.3470926	0.0865208	**
Hose	-0.1360636	0.0648129	*	-0.1740819	0.0630326	**
Sprinkler	0.0600144	0.1283189		0.0406933	0.133043	
Water softener	0.0931076	0.243146		-0.0043498	0.2310298	
ACORN A	0.1037189	0.1084513		0.0402391	0.1030392	
ACORN B	-0.0614428	0.1059498		-0.0917561	0.1028327	
ACORN C	-0.0390381	0.1082942		-0.0660316	0.1045914	
ACORN D	0.149765	0.0922577		0.1028732	0.0880031	
ACORN E (base)	0	0		0	0	
ln(Water consumption)	-0.4035086	0.036242	**			
Sample size	2776			2776		
Log pseudolikelihood	-1303.2312			-1382.0694		
Pseudo R^2	0.2558			0.2107		

Dependent variable: *Meter* (the water-metering dummy)
Heteroscadasticity-robust standard errors are shown.
* Significant (p<0.05); ** Strongly significant (p<0.01)

Next, the coefficients of Model 2b could be interpreted as follows:

- The coefficient on *RV* is significantly positive. That is, the larger the *RV*, the more likely the household would install a water meter. This would endorse our earlier Proposition 2 (Section III-1-e).
- The coefficient on *year-built* is significantly positive. Hence the newer the properties, the more likely they have a water meter. This is expected because installation of meters to new properties has become routine in recent years.
- The negative coefficient on *occupancy* together with the positive one on *occupancy-squared* implies an inverse and convex relationship between occupancy and switching to metering. This is plausible because, holding other conditions equal, higher occupancy implies higher water consumption (by Model 1b), which would in turn reduce propensity to opt for metering (by Proposition 1).

c. Endogeneity problem of the demand effect of metering

In Section III-1-d, we have theorised that the more water the household would consume when flat-charged, the less likely they are to opt for metering (Proposition 1). A ramification of this proposition is an endogeneity problem when estimating the DEM, which is explained by **Fig.11** below.

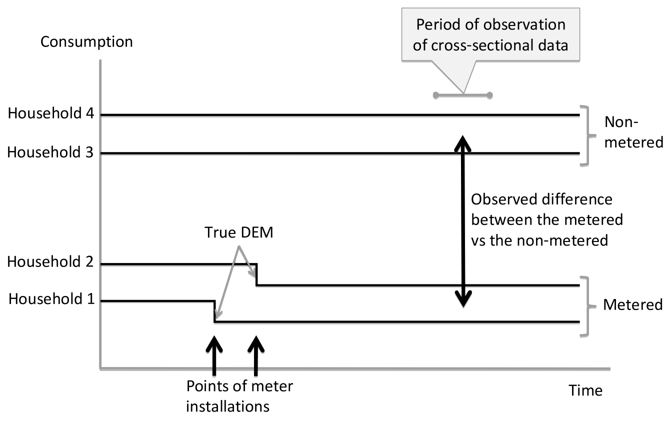

Fig.11 Schematic diagram for the DEM and observed differences
(Source: modified after Kyle (2009: 58))

Fig.11 schematically presents time paths of water consumptions of four representative households. Households 1 and 2 represent low-consumption households, which opt for metering, whilst Households 3 and 4 stand for high-consumption households, which opt out. Since the DEM is defined as the fall in water consumption when a household installs a meter, it should be measured as the small dips in consumption labelled “True DEM”.

On the other hand, since the cross-sectional data were collected *after* the households made their decisions, and observe consumptions of different households at a single period of time, the observed difference between the metered vs the non-metered should be the big double-pointed arrow on the right side of **Fig.11**. As such, the observed mean difference in the OLS Model 1b (42.9%, **Table 4**) could grossly overestimate the true DEM.

d. Model 3: the simultaneous equation model

Our previous discussions have suggested that the econometric models 1b and 2b are not independent ones, but rather a system of equations in which the metering dummy is jointly determined, or endogenous. Hence we next set out to construct a simultaneous equation model that can incorporate such interdependency of equations.

In Section IV-2-c, we focused our attention on the endogeneity of the water-metering dummy, which is a qualitative response (QR) variable. When endogenous variables are QR ones, we need to address two important issues, namely coherency and identification (Heckman, 1978; Amemiya, 1978).

(1) Coherency

Coherency condition[18] is a requirement that there be a one-to-one mapping between the vector of values taken by the stochastic disturbance terms appearing in the model, and the vector of realisations of the endogenous variables. Coherency usually requires restrictions over and above identification restrictions. We now aim to derive the coherency condition using a simplified system of equations. We assume:

$$y = \alpha d + u \tag{6}$$

$$d^* = \beta y + \nu \tag{7}$$

where: y is water consumption,
d is water-metering dummy,
d^* is the propensity to opt for metering (d = 1 if d^*>0; d = 0 otherwise),
α is a negative effect of metering on consumption, which represents the DEM,
β is a negative effect of consumption on propensity to switch to metering,
u and v are disturbance terms.

If a household has no meter, then d = 0, and hence equation (6) becomes $y = u$. Inserting this into (7), we have: $d^* = \beta u + \nu$. Since d = 0, it must be that:

$$\beta u + \nu \leq 0$$

or
$$\nu \leq -\beta u \tag{8}$$

If, by contrast, a household has a meter, then d = 1, and hence equation (6) becomes $y = \alpha + u$. Inserting this into (7), we have: $d^* = \alpha\beta + \beta u + \nu$. Since d = 1, it must be that:

$$\alpha\beta + \beta u + \nu > 0$$

or
$$\nu > -\alpha\beta - \beta u \tag{9}$$

The above conditions (8) and (9) are represented by hatched areas in a u-v plane (**Fig.12**). Since both α and β are negative, $-\alpha\beta$ is negative. This implies the two hatched areas have an overlapping region (**Fig.12**). This in turn suggests that, if u and v happen to take values within this region, a household is both metered and non-metered at the same time.

---

[18] This is referred to as “conditions for existence of the model” in Heckman (1978: 935).

This is clearly contradictory, and therefore we must eliminate this region. This is indeed the requirement of coherency, which demands that, for every pair (u, v), there must be a unique pair (d, y). Hence we impose a restriction $\alpha\beta = 0$, that is, either $\alpha = 0$ or $\beta = 0$.

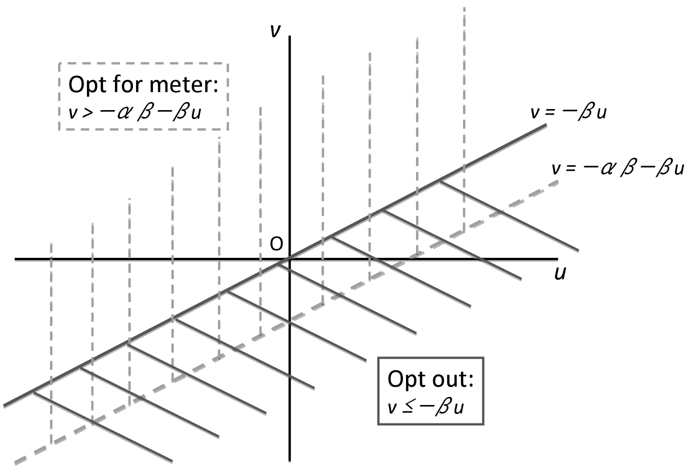

Fig.12 An incoherent case for the simultaneous equation model

We choose to set $\beta = 0$ so that $\alpha \neq 0$. This implies we allow consumption to depend on metering, but not vice versa. In other words, the DEM should be non-zero. We may justify this firstly because we have theorised in Chapter III that there exists a positive DEM, and it is our focus of econometric analyses to explore the magnitude of DEM. Secondly, consumption in the cross-sectional data is observed *after* the decision is made (see **Fig.11**), whereas our theory suggests that the decision would depend on the consumption *before* the decision is made (Proposition 1). Therefore, allowing the *post*-decision consumption to affect the decision itself (i.e. setting $\beta \neq 0$) would be not only illogical but also incompatible with our theory[19].

(2) Identification

A system of equations would be identified if there were any way to obtain unique estimates of parameters of the model. In order for the system to be identified, we need to meet the *order condition* (which is a necessary condition for identification), and the *rank condition* (which is a sufficient condition).

First, the order condition requires: [the number of exogenous variables excluded from the equation] ≥ [the number of endogenous variables included on the RHS (right-hand side)]. Here our first equation is:

$$y_i = \gamma d_i + \beta' x_i + u_i \qquad i = 1, \ldots, n \tag{10}$$
$$u_i \sim \mathrm{N}(0, \sigma^2)$$

where endogenous variable on the RHS is d_i. (Other explanatory variables x_i are taken as exogenous.)

The second equation is:

$$d_i^* = \alpha' z_i + v_i \qquad i = 1, \ldots, n \tag{11}$$
$$v_i \sim \mathrm{N}(0, 1)$$
$$d_i = 1 \qquad \text{if } d_i^* > 0;$$
$$d_i = 0 \qquad \text{if } d_i^* \leq 0$$

where the endogenous variable y has been excluded from the RHS to meet the coherency condition.

Therefore, to meet the order condition, at least one exogenous variable must be excluded from equation (10). Thus, we choose to exclude *RV* and *year-built* from equation (10) because: (1) both variables have significant effects on d^* (see Model 2b, **Table 6**); and (2) there are no inherent reasons to believe that these variables, which represent characteristics

[19] Stating this from a slightly different perspective, we claim that: for a household with given characteristics, there are two different consumption levels, one for the metered and the other for the non-metered. Since the consumption is not uniquely determined, it is meaningless to consider its effect on another variable.

of the properties, have *direct* effects on water consumption[20].

Having met the order condition, we need to check for the rank condition. Hence we write a matrix of parameters as follows:

$$\begin{bmatrix} -1 & \gamma & 0 & 0 & \beta_1 & \beta_2 & \cdots & \beta_{14} \\ 0 & -1 & \alpha_1 & \alpha_2 & \alpha_3 & \alpha_4 & \cdots & \alpha_{16} \end{bmatrix} \tag{12}$$

where: Rows 1 and 2 indicate parameters of equations (10) and (11), respectively,

Columns (from left to right) are parameters of *y, d (or d*), RV, year-built*, and the other explanatory variables.

For equation (10), we require: $rank[\alpha_1\ \alpha_2] \geq 1$, which is met.

For equation (11), we require: $rank[-1] \geq 1$, which is met.

Hence the rank condition is satisfied.

(3) Simultaneous equation model

In summary, we have constructed a **simultaneous equation model 3** comprising equations (10) and (11), in which *RV* and *year-built* are excluded from equation (10), and *y* from equation (11). In other words, we set to combine our earlier Models 1b and 2b. Because d_i is now endogenous in equation (10), we shall replace d_i by the estimate of d_i obtained through equation (11), which acts as an instrumental variable. This model is also called the **treatment-effects model** (Greene, 2008: 889), which could overcome a problem of overestimating the treatment effect (which is the DEM in our context) in the presence of self-selection issues.

The model disturbances *u* and *v* are assumed to follow a bivariate normal distribution with zero mean and covariance matrix:

$$\begin{pmatrix} \sigma^2 & \rho\sigma \\ \rho\sigma & 1 \end{pmatrix} \tag{13}$$

The difference in consumptions between the metered and the non-metered is, then (Greene, 2008: 890):

$$E[y_i | d_i = 1] - E[y_i | d_i = 0] = \gamma + \rho\sigma\left[\frac{\phi_i}{\Phi_i(1-\Phi_i)}\right] \tag{14}$$

where: ϕ is the standard normal density function,

Φ is the standard normal cumulative distribution function.

Equation (14) implies that, if the correlation between the disturbances, ρ, is zero, the OLS model would give an unbiased estimator of the treatment effect γ. On the other hand, if ρ is significantly *negative*, the second term of the right-hand side of (14) would bias the OLS estimator *away* from zero, since γ would also be negative. Hence, the OLS estimator would *over*estimate γ (in the absolute value term) when ρ is negative.

The results of estimations are summarised in **Table 7**. First of all, the reported λ (=$\rho\sigma$) is significantly negative. This implies, through equation (14), that the OLS estimator would overestimate the treatment effect. This is endorsed by a comparison of estimates of the *meter* coefficient between Model 1b (the OLS estimator) of 42.9%, and Model 3 (the treatment-effects estimator) of 9.5%[21]. This would give us enough reason to prefer Model 3 to Model 1b in estimating the DEM.

3 Summary

This chapter has attempted to estimate the DEM using a cross-sectional data set. Since our theory has suggested an endogeneity problem on the *meter* dummy, we extended our analysis to the treatment-effects model, which could accom-

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[20] After all, it is the persons and appliances present in the property, not the property itself, which consume water. Although a significant effect of *RV* on consumption was observed in the OLS Model 1a (**Table 4**), we may well regard this as an indirect effect via incomes etc.

[21] However, unfortunately it is *not* significantly different from zero at the 5% level.

modate the problem. The estimated results indeed suggested such endogeneity, and hence the model's superiority over the OLS model in estimating the DEM. However, the conclusion remained indecisive, as the metering dummy was insignificant in the treatment-effects model. This leads us to explore panel data, which is a theme of the next chapter.

Table 7 Estimated parameters for three models

	Model 1b (OLS)		**Model 2b** (probit)		**Model 3** (treatment-effects)	
Variables	Coeff.	Std. err.	Coeff.	Std. err.	Coeff.	Std. err.
ln (Water consumption)						
Constant	9.568	0.111 **			9.288	0.113 **
Meter	-0.429	0.038 **			-0.095	0.076
Occupancy	0.452	0.044 **			0.544	0.049 **
Occupancy-squared	-0.039	0.006 **			-0.047	0.007 **
Washing machine	0.489	0.092 **			0.520	0.076 **
Dishwasher	0.115	0.037 **			0.081	0.040 *
Dual-flush toilet	0.031	0.042			0.036	0.046
Power shower	0.122	0.037 **			0.095	0.039 *
Wash vehicle	0.110	0.041 **			0.136	0.046 **
Hose	0.157	0.036 **			0.165	0.036 **
Sprinkler	0.072	0.056			0.049	0.071
Water softener	0.302	0.097 **			0.267	0.122 *
ACORN A	0.226	0.058 **			0.178	0.057 **
ACORN B	0.083	0.057			0.061	0.058
ACORN C	0.080	0.064			0.072	0.062
ACORN D	0.106	0.055			0.085	0.052
ACORN E (base)	0	0			0	0
ρ					-0.265	0.051
σ	0.819				0.829	0.012
λ					-0.220	0.044
Meter						
Constant			0.008	0.171	-0.038	0.179
Rateable value			0.005	0.000495 **	0.005	0.000 **
Year-built			0.006	0.001 **	0.006	0.001 **
Occupancy			-0.869	0.074 **	-0.843	0.088 **
Occupancy-squared			0.071	0.011 **	0.067	0.014 **
Washing machine			-0.290	0.121 *	-0.305	0.121 *
Dishwasher			0.009	0.073	-0.014	0.073
Dual-flush toilet			-0.113	0.080	-0.101	0.083
Power shower			0.152	0.066 *	0.144	0.067 *
Wash vehicle			-0.347	0.087 **	-0.337	0.084 **
Hose			-0.174	0.063 **	-0.190	0.063 **
Sprinkler			0.041	0.133	0.039	0.124
Water softener			-0.004	0.231	-0.014	0.209
ACORN A			0.040	0.103	0.031	0.103
ACORN B			-0.092	0.103	-0.086	0.105
ACORN C			-0.066	0.105	-0.065	0.111
ACORN D			0.103	0.088	0.109	0.092
ACORN E (base)			0	0	0	0
Log L				-1382.0694		-4747.0581

Sample size is 2776 in all models.
Models 1b and 2b show heteroscadasticity-robust standard errors.
* Significant ($p<0.05$); ** Strongly significant ($p<0.01$)

V Econometric analyses of water consumption with panel data of households

This chapter turns our focus on panel data, which is a set of observations on many households repeated over a period of time. Hence it simultaneously has characteristics of cross-sectional and time-series data. The fundamental advantage of panel data analysis is that it allows us to estimate the partial effects of explanatory variables, after taking out the individual (household) specific effects, or the heterogeneity. This feature is particularly useful for us, because it is what we are aiming for in estimating the DEM. We begin by discussing the modelling frameworks, which is followed by data descriptions and econometric analyses.

1 Modelling framework

a. Three models

The basic framework for panel data analysis is a regression model of the form (Greene, 2008: 182):

$$y_{it} = x'_{it}\beta + z'_i\alpha + \varepsilon_{it} \tag{15}$$

where: y_{it} is log of water consumption,
x_{it} is a $k\times1$ vector of (observed) explanatory variables (not including a constant term), which consist of both household-specific variables (e.g. *ACORN* variables) and time-dependent variables (e.g. water consumption),
β is a vector of parameters,
$z'_i\alpha$ is the household effect where z_i contains a constant term and a set of household-specific variables that are unobserved,
ε_{it} is a disturbance term,
and subscripts i (i=1,…,n) and t (t = 1,…,T) indicate household and time, respectively.

First, if z_i contains only a constant term (i.e. there would be no unobserved heterogeneity across households), the model (15) is reduced to:

$$y_{it} = x'_{it}\beta + \alpha + \varepsilon_{it} \tag{16}$$

And hence the OLS model gives consistent and efficient estimates. This is called the **pooled regression model**.

Second, if unobserved household-effect variables in z_i are correlated with x_{it}, the OLS estimator is biased and inconsistent because of the omitted variables in z_i. In this case, the following **fixed-effects model** gives consistent estimator:

$$y_{it} = x'_{it}\beta + \alpha_i + \varepsilon_{it} \tag{17}$$

where the heterogeneity across households is captured in differences in the constant term α_i.

The advantage of this model is that it gives consistent (albeit inefficient at times) estimator whether z_i is correlated or uncorrelated with x_{it}. On the other hand, the disadvantage is that we have to estimate β as well as α_i on dummies for every household, which implies we need to sacrifice a large number of degree of freedom when the number of households is large. This may render this model inefficient if we have another model that is also consistent. Besides, since the effects of any time-invariant variables in x_{it} would be absorbed in α_i, we cannot estimate their effects on the dependent variable.

Third, if we could take stronger assumptions that the unobserved heterogeneity z_i is uncorrelated with x_{it} in any way, we can formulate the **random-effects model**:

$$y_{it} = x'_{it}\beta + \alpha + u_i + \varepsilon_{it} \tag{18}$$

where: u_i expresses a household-specific disturbance, which is invariant in the time period.
Specifically, we assume the following about the disturbances:

$$
\begin{aligned}
&E(u_i) = E(\varepsilon_{it}) = 0 \\
&Var(u) = E(u_i^2) = \sigma_u^2 \\
&Var(\varepsilon) = E(\varepsilon_{it}^2) = \sigma_\varepsilon^2 \\
&E(u_j \varepsilon_{it}) = 0 \qquad \textit{for all i, t, j} \\
&E(\varepsilon_{it}\varepsilon_{js}) = 0 \qquad \textit{if } i \neq j \textit{ or } t \neq s \\
&E(u_i u_j) = 0 \qquad \textit{if } i \neq j
\end{aligned} \tag{19}
$$

where: σ^2_u indicates the between variance, and σ^2_ε the within variance.

The advantage of this model is that it reduces the number of estimated parameters (which are β and α only), and hence gives an efficient estimator in preference to the fixed-effects model, provided that z_i (and hence u_i) are uncorrelated with x_{it}. Moreover, effects of time-invariant variables in x_{it} can now be estimated in the random-effects model. On the other hand, the disadvantage is that it gives inconsistent estimator when u_i is in fact correlated with x_{it}.

b. Criteria for model selection

Having introduced the three models for panel data, we need to have criteria for judging which model is favourable. First, to find whether the fixed-effects model is preferred to the pooled regression model, we conduct the following **F-test**:

$$\mathrm{H}_0\text{:} \;\; \alpha_1 = \alpha_2 = \alpha_3 = \cdots = \alpha_n$$

That is, there is no systematic difference in household dummies.

If H_0 is true, then the pooled regression model gives the consistent and efficient estimator, and hence we prefer this to the fixed-effects model, which is inefficient. By contrast, when H_0 is rejected, the pooled regression estimator is inconsistent whilst the fixed-effects estimator is consistent. Hence we prefer the fixed-effects model to the pooled regression model.

Thus, we conduct the F-test, where:

- Unrestricted model is the fixed-effects model; and restricted model is the pooled regression model
- Number of restrictions: $n - 1$
- Degree of freedom for the unrestricted model: $nT - n - k$, where nT is the sample size, and $n + k$ is the number of parameters in the fixed effect model (k is the number of parameters in β).

Hence we have the F ratio for the test:

$$F(n-1, nT-n-k) = \frac{(R_U^2 - R_R^2)/(n-1)}{(1-R_R^2)/(nT-n-k)} \tag{20}$$

where: R^2_U is the coefficient of determination for the unrestricted model,
R^2_R is that for the restricted model.

Second, we turn to the criteria for choosing between the fixed-effects model and the random-effects model. One of the tests for this purpose is the **Hausman test** (Greene, 2008: 209). It sets the null hypothesis:

H_0: there is no correlation between the included variables x_{it} and u_i

- If H_0 is true, both the fixed-effects and random-effects models are consistent, but the former is inefficient. Hence we prefer the latter to the former.
- If H_0 is false, the fixed-effects model is consistent but the random-effect model is inconsistent. Hence we prefer the former to the latter.

These in turn imply that, if H_0 is true, there should be no systematic difference between the estimators of the two models. This can be tested with the statistics:

$$H = (\hat{\beta}_{FE} - \hat{\beta}_{RE})' \left[\hat{V}(\hat{\beta}_{FE}) - \hat{V}(\hat{\beta}_{RE})\right]^{-1} (\hat{\beta}_{FE} - \hat{\beta}_{RE}) \tag{21}$$

which is asymptotically distributed as $\chi^2(k)$ under H_0

where: $\hat{\beta}_{FE}$ is the fixed effects estimator, and $\hat{\beta}_{RE}$ is the random effects estimator.

2 Descriptions of data

The panel data is extracted from the same survey described in Chapter IV. The data between January 1996 and May 2001 were extracted and compiled as monthly water consumption data. However, not all the sample households are surveyed throughout this period, and hence the panel is unbalanced. The sample contained a total of 595 households, which consists of 110 of the metered, 25 of the non-metered (both throughout the observation period), and 460 of the optant (those that switched from non-metered to metered status during the observation period[22]) (**Table 8**).

Table 8 Descriptive statistics of monthly water consumption

Household types	Sample size	Mean	Std. deviation	per day[1)]
Non-metered throughout	25	10,080	5,147	336
Optant	460	7,043	3,681	235
of which (before switching)		7,639	3,881	255
of which (after switching)		6,491	3,547	216
Metered throughout	110	6,698	4,016	223
Whole sample	595	7,107	3,861	253

Unit: litres per month
1) (mean monthly consumption) / 30

A comparison between mean consumptions of the non-metered (10,080) and the optant (before switching) (7,639) implies that there is indeed the self-selection issue (i.e. Proposition 1): the more water the household consumes when flat-charged, the less likely they switch to metering. Another comparison between the mean consumption of the optant before switching (7,639) and that after switching (6,491) provisionally indicates that the optant households saved water by 15.0% on average upon switching. (Both these two differences are significant at the 1% level[23].)

Fig.13 shows the time path of monthly water consumption that is averaged over the whole households. It implies a downward trend of consumption over time. Hence we include the time-trend variable (ranging from "one" for January 1996 to "65" for May 2001) in the explanatory variable. It also reveals large seasonal fluctuations of consumption around the trend. We therefore include the month dummies in the explanatory variable.

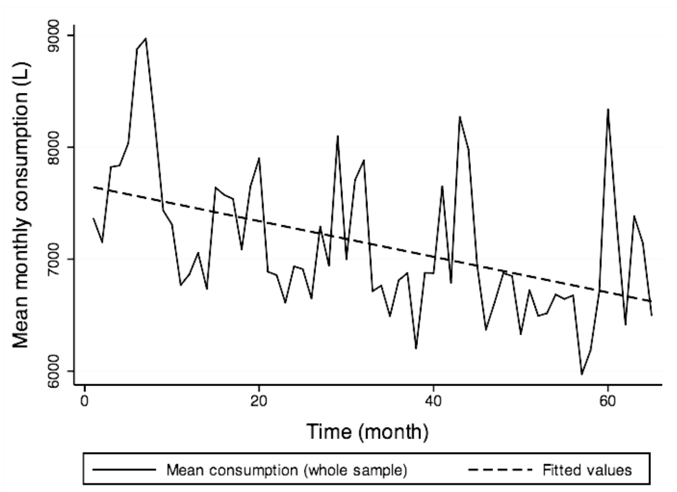

Fig.13 Time trend of mean monthly water consumption of households

[22] This study specifically calls this group of households "optants", although, in general, the term broadly means households that choose to switch to metering at any time period.
[23] The *t*-statistics of the two comparisons (H_0: no difference in means) are 3.00 (p=0.0028) and 4.69 (p=0.0000), respectively.

A further investigation on time trends for each category of households (**Fig.14**) indicates that the downward trend is particularly obvious for the non-metered and the optant[24]. Furthermore, the fitted line of the non-metered is far above those of the other two categories, which would again endorse the self-selection issue. Another interesting feature is that seasonal fluctuations of the non-metered appear to be much wider than the other two. This might be expected because the non-metered have less incentive to save water for "discretionary uses" such as watering gardens during the summer, which would push up their water consumptions during summer to very high levels, relative to the metered[25].

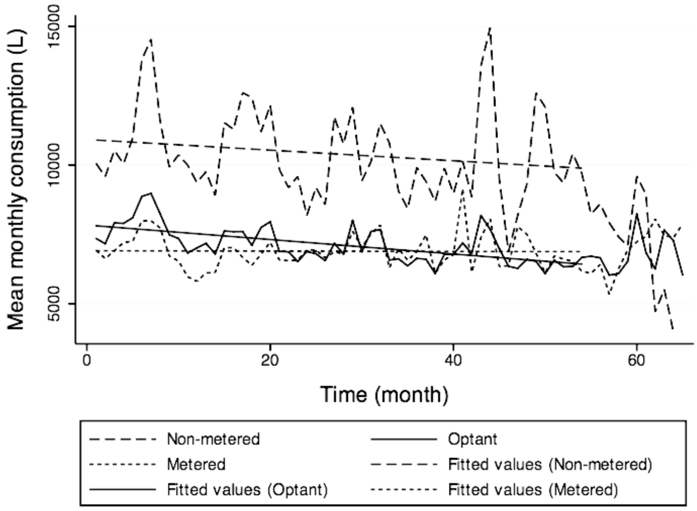

Fig.14 Time trend of mean monthly water consumption of households of each category

3 Econometric models with panel data

a. Models 4a and 5a: the fixed-effects and the random-effects models

Following our previous discussions, we now set to build two models: **the fixed-effects model 4a** (equation 17) and **the random-effects model 5a** (equation 18). We omit the descriptions of the explanatory variables, as they are basically the same as those of the cross-sectional models in Chapter IV (**Table 1**). The only new variables added here are: *bedroom*, which indicates the number of bedrooms a household possesses; and the time-trend and month-dummy variables that have been described in Section V-2.

The results of estimation are reported in **Table 9**. According to the test statistics of the F-test (equation 20) and the Hausman test (equation 21), we reject H_0 at the 1% level for both tests. We therefore have strong evidences to prefer the fixed-effects model to the pooled regression model (F-test); and to prefer the fixed-effects model to the random-effects model (Hausman test). Hence we conclude that we select the fixed-effects model in preference to the other two[26].

Next, the coefficients of Model 4a are interpreted as follows:

- Most importantly, the partial effect of *meter* is now estimated at 13.2% on average, which is significant at the 1% level, with a 95% confidence interval of 10.2 − 16.1%. We may well recognise this as a consistent estimator of the DEM, as household-specific effects have now been taken out, as discussed in Section V-1.

[24] In **Fig.14**, the fitted lines were drawn on data in a time period t<55, as the later period appears to deviate from the overall trend for unknown reason.

[25] We should be mindful, however, that this observation might instead be attributed to the relatively small sample size of non-metered households (**Table 8**).

[26] Nevertheless, it should be noted that the "between" and "overall" R-squares of **Model 4a** are smaller than those of **Model 5a**. Thus, in terms of the explaining power of the models, the random-effects model would be superior to the fixed-effect model, although the Hausman test suggests the former would be inconsistent.

Table 9 Estimated fixed-effects and random-effects models for water consumption (1)

	Model 4a (fixed-effects)			**Model 5a (random-effects)**		
Variables	Coefficients	Std. errors		Coefficients	Std. errors	
Constant	8.114428	0.0581325	**	7.266677	0.0978068	**
Meter	-0.1316871	0.0152048	**	-0.1462646	0.0148133	**
Occupancy	0.5290052	0.0458462	**	0.6236188	0.0416748	**
Occupancy-squared	-0.082321	0.0084821	**	-0.0921893	0.0077984	**
Bedroom				0.1591361	0.0273909	**
Dishwasher				0.1998858	0.0571471	**
Dual-flush toilet				-0.0138329	0.0612355	
Wash vehicle				0.0457376	0.0222979	*
Hose				0.1586629	0.0475057	**
Sprinkler				0.17611	0.096847	
Water softener				0.1681517	0.1101591	
ACORN A				0.0473051	0.0740658	
ACORN B				0.1920928	0.0803895	*
ACORN C				0.1534503	0.0839895	
ACORN D				0.0900033	0.066017	
ACORN E (base)				0	0	
Time trend	-0.0034304	0.0003028	**	-0.0030789	0.0002982	**
January (base)	0	0		0	0	
February	-0.0303234	0.019247		-0.0302155	0.0192712	
March	0.0840946	0.019165	**	0.0844717	0.0191885	**
April	0.0484122	0.0192883	*	0.0493768	0.0193103	*
May	0.0804886	0.0194318	**	0.0811884	0.0194539	**
June	0.0552308	0.0193877	**	0.0555583	0.0194088	**
July	0.1188382	0.019548	**	0.119539	0.0195707	**
August	0.091189	0.0196208	**	0.0918691	0.0196436	**
September	-0.0064381	0.019615		-0.0059752	0.019638	
October	-0.0092221	0.0201182		-0.0082683	0.0201416	
November	-0.0190788	0.0207709		-0.0176264	0.0207948	
December	0.01157	0.0204629		0.0118214	0.0204875	
σ_u	0.60575869			0.48544146		
σ_ε	0.66995324			0.66995324		
R^2 (within)	0.0308			0.0305		
R^2 (between)	0.3853			0.4405		
R^2 (overall)	0.1846			0.2407		
Sample size (*obs*)	27242			27242		
Sample size (*n*)	595			595		
Sample size (*T*; max)	65			65		
F-test (p-value)	23.36	(0.0000)				
Hausman test (p-value)				68.32	(0.0000)	

Dependent variable: ln (*water consumption*)
* Significant (p<0.05); ** Strongly significant (p<0.01)

- The coefficients on *occupancy* and *occupancy-squared* again imply a concave relationship between occupancy and water consumption[27] as discussed in Section VI-2-a.
- Negative sign of the time-trend coefficient implies that water consumption is declining over time at a rate of 0.34% per month on average. It should be noted that this effect is observed after taking out the partial effect of metering, and hence indicates an underlying trend of decline in water consumption irrespective of water-meter installation. This might be expected because, for instance, a stock of accommodations in the region might undergo continual renovations in which water leaks within properties would be reduced, regardless of advancement of water metering.

[27] Likewise, *bedroom* in Model 5a, which may be closely related to occupancy, would have strongly positive effect on water consumption.

It might also be attributed to the change in households' tastes (such as widespread concerns for the environment).

- The month dummies from March to August are significant, whilst the other ones are insignificant. To depict the seasonal variations more clearly, coefficients and 95% confidence intervals of the month dummies are shown in **Fig.15**. It reveals that water consumptions between March and August are distinctively higher than the other months, with a peak in July. This would chiefly be attributed to greater water uses for showers and gardening in summer months.

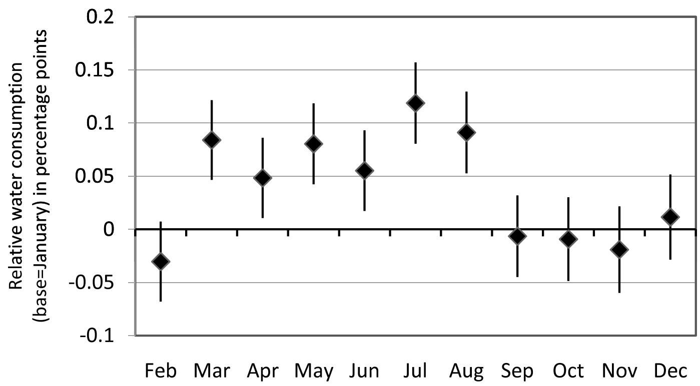

Fig. 15 Seasonal variations of water consumption

Note: Dots indicate the average; solid lines 95% confidence intervals.

b. Models 4b and 5b: incorporating rateable values

In Section III-1-g, we theorised that there is an inverse relationship between the RV and the DEM (Proposition 3). Yet in Section IV-2-d-(2), we argued that the RV is deemed to have no direct effect on water consumption. Thus, one of the techniques to accommodate the RV in our current models is to include an interaction term, that is, (*meter*)/(*RV*), or *morv* for short, to express an indirect effect that the RV might have on water consumption.

Hence **Table 10** reports the estimated results on the same models as 4a and 5a, except that we now include *morv* in the explanatory variables. We name these as **Models 4b** and **5b**, respectively. (As in Section V-3-a, Model 4b (fixed-effects) is preferred to both the pooled regression model and Model 5b (random-effects), according to the F-test and the Hausman test.) The new variable *morv* turns out to be significant at the 1% level. Hence, the DEM could now be estimated (in Model 4b) as:

$$DEM = -\left[\frac{\partial(\hat{\ln}(y))}{\partial(meter)}\right]\times 100(\%) = -2.69 + \frac{2794}{RV}(\%) \tag{22}$$

Thus, the inverse relationship between the two variables is indeed demonstrated. A simulated relationship based on this estimate (**Fig.16**) suggests that the DEM is very large for households with lower RV, but decreases towards zero as the RV increases. This might chiefly be attributed to different MRS for water across households (see **Fig.7**), which suggests wealthier households have less incentive to save water relative to poorer ones[28]. It furthermore implies that installing water meters to wealthier households (with higher RV) would bring little benefits to society in terms of water savings, which is the main issue in Chapter VI. Meanwhile, incorporating the RV in Model 4b enhances the explaining power of model, as it has higher "between" and "overall" R^2 than Model 4a (**Tables 9** and **10**).

[28] It might alternatively be explained as follows: since wealthier households (with higher RV) had paid higher tariffs before switching, they would need less reduction in water consumption upon switching in order to save expenditure on water, relative to the poor (with lower RV).

Table 10 Estimated fixed-effects and random-effects models for water consumption (2): with the rateable value

	Model 4b (fixed-effects)			**Model 5b (random-effects)**		
Variables	Coefficients	Std. errors		Coefficients	Std. errors	
Constant	8.127029	0.0581837	**	7.366932	0.0967039	**
Meter	0.0268924	0.0351975		0.035148	0.0329399	
Meter/RV (morv)	-27.93628	5.88713	**	-32.89997	5.510324	**
Occupancy	0.5015164	0.0458671	**	0.5929481	0.0416176	**
Occupancy-squared	-0.0772183	0.0084835	**	-0.0863215	0.0077807	**
Bedroom				0.1346948	0.0270522	**
Dishwasher				0.1903318	0.0556541	**
Dual-flush toilet				-0.0154021	0.0592827	
Wash vehicle				0.0457915	0.0215909	*
Hose				0.1512335	0.0464058	**
Sprinkler				0.1681884	0.0937116	
Water softener				0.1568604	0.1065951	
ACORN A				0.0237185	0.0717766	
ACORN B				0.176324	0.0782796	*
ACORN C				0.1831709	0.0818256	*
ACORN D				0.0866265	0.0640377	
ACORN E (base)				0	0	
Time trend	-0.0034074	0.0003027	**	-0.0030095	0.0002981	**
January (base)	0	0		0	0	
February	-0.0302838	0.0192861		-0.0301203	0.0193191	
March	0.0831841	0.0192033	**	0.0835956	0.0192355	**
April	0.0476377	0.0193281	*	0.048651	0.0193587	*
May	0.0798707	0.0194642	**	0.0807757	0.019495	**
June	0.0546062	0.0194211	**	0.0550113	0.0194509	**
July	0.1193418	0.0195875	**	0.1200046	0.019619	**
August	0.0893197	0.0196567	**	0.0899642	0.0196883	**
September	-0.0066699	0.0196554		-0.0062824	0.0196872	
October	-0.0045153	0.0201605		-0.0034349	0.0201929	
November	-0.0188756	0.020802		-0.0173153	0.020835	
December	0.0114862	0.0204916		0.0120286	0.0205254	
σ_u	0.58948799			0.46863903		
σ_ε	0.66840986			0.66840986		
R^2 (within)	0.0303			0.03		
R^2 (between)	0.4373			0.454		
R^2 (overall)	0.2116			0.2471		
Sample size (*obs*)	27013			27013		
Sample size (*n*)	585			585		
Sample size (*T*; max)	65			65		
F-test (p-value)	22.89	(0.0000)				
Hausman test (p-value)				78.88	(0.0000)	

Dependent variable: ln (*water consumption*)
* Significant ($p<0.05$); ** Strongly significant ($p<0.01$)

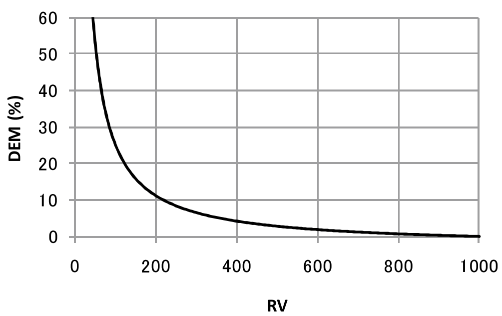

Fig.16 Simulated relationship between the rateable value and the DEM

4 Summary

The fixed-effects model with panel data allowed us to estimate the partial effect of metering after taking out the household-specific effects. Consequently, we successfully estimated the DEM as 13.2% on average, with a narrow 95% confidence interval. This is close to the recent estimate of 13% for England and Wales (Environment Agency, 2008a: 11), and within a range 5−23% of previous estimates for various parts of UK (summarised by Kyle (2009: 23)).

Nevertheless, further improvement of the model by incorporating an interaction term of *meter* and *RV*, revealed that the DEM would differ considerably across households. Hence the average DEM mentioned above should be treated as a rough guide rather than the exact prediction.

VI Social welfare of water metering

In previous chapters, we have found that wealthier households (with higher RV) are more likely to opt for metering, yet they would show up smaller DEM once a meter is installed. This suggests socially inefficient outcome, because social benefits in terms of water savings would be small relative to the cost of installing meters. The underlying cause of this “adverse selection” problem would be the current uniform metered charges: households pay the same volumetric (per-volume) charge irrespective to their DEM or latent propensity to switch to metering. This implies that we might achieve socially more efficient outcome by differentiating metered charges across households (or introducing progressive pricing). Thus, this chapter empirically seeks progressive charging schemes following a theoretical work of Cowan (2010).

1 Theoretical model

This section summarises the condition to achieve socially efficient outcomes when a water company knows households’ types[29] regarding water consumption, after Cowan (2010: 803-807). To begin with, the objective of a water company, being a public body, is to maximise social welfare by introducing meters. Therefore, for every meter installed, they aim to attain larger social welfare relative to that before installation.

Hence we should have:

$$u(x^m(t),t) - w\,x^m(t) - m \geq u(x^f(t),t) - w\,x^f(t) \tag{23}$$

where: $x^m(t)$ and $x^f(t)$ are water consumptions of the metered and the non-metered, respectively, which depend on household’s type t,
$u(.)$ is household’s utility derived from water consumption, which depends on t,
w is marginal cost of producing tap water,
m is marginal cost of meter installation.

The left-hand side of equation (23) expresses social welfare after meter installation, whilst the right-hand side that before installation.

Equation (23) could be modified as:

$$u(x^m(t),t) - u(x^f(t),t) + w\left[x^f(t) - x^m(t)\right] \geq m$$

or

$$u(x^m(t),t) - u(x^f(t),t) + w\left[DEM(t)\right] \geq m \tag{24}$$

The left-hand side of equation (24) expresses the social benefit of metering (with the third term indicating avoided production costs through water saving), whilst the right-hand side the social cost of metering.

Meanwhile, the objective of a household is to maximise utility. Hence the “participation constraint” of household to

[29] We will later attribute the “type” to the rateable value, which is a continuous variable.

switch to metering is[30]:

$$u(x^m(t),t) - T^m(x^m(t),t) \geq u(x^f(t),t) - T^f(t) \tag{25}$$

where: $T^m(.)$ and $T^f(.)$ are annual water tariffs[31] levied on the metered and the non-metered, respectively, which depend on t.

The household's decision to switch to metering achieves social efficiency if both equations (24) and (25) hold together. A sufficient condition to achieve this is:

$$T^{m*}(x^m(t),t) - T^f(t) = m - w[DEM(t)]$$

or

$$T^{m*}(x^m(t),t) = T^f(t) + m - w[DEM(t)] \tag{26}$$

We call T^{m*} **the "first-best" metered tariff**. Equation (26) roughly implies that the larger the DEM of a household, or the smaller the non-metered tariff T^f, the *lower* the metered charge for that household should be, since it incentivises them to switch to metering, thereby attaining more socially efficient outcomes. The equation also implies that T^{m*} gives the water company a financially neutral position with respect to metering costs (m) and benefits ($w[DEM]$). In other words, T^{m*} should be higher than T^f if the metering costs exceeds the benefits (avoided production costs), so that the water company could recover any financial loss from meter installation.

2 Empirical model

a. Modelling framework

We now proceed to develop an empirical model for the above theory, to find a desirable metered charging scheme. First of all, we assume that household's type could be modelled by their rateable value. This assumption is deemed simplistic, because households' water consumptions and metering decisions could be influenced by a number of other factors, as we have discovered. However, we should be mindful that we ought to select a household characteristic that is actually accessible to water companies to satisfy the "complete information" assumption in the theory. Hence choosing rateable values would be sensible, as water companies indeed have such information when households are non-metered, and our main concern here is social welfare from the perspective of household's income.

Next we empirically express equation (26) in terms of RV. Throughout this chapter, we use the same cross-sectional dataset as Chapter IV. We begin by estimating a relationship between the non-metered water consumption x^f and the rateable value[32]. The scattered diagram for them (**Fig.17**) is understandably dispersed due to the noises coming from unexplained factors, but we nevertheless detect a concave pattern from the Lowess smoother, which provides locally weighted scatterplot smoothing. Hence we propose a quadratic function:

$$x^f = \beta_0 + \beta_1(RV) + \beta_2(RV)^2 \tag{27}$$

According to the OLS estimation for the non-metered households only (**Table 11**), we have an estimate for equation (27):

$$\hat{x}^f = 49860.58 + 290.38 \times RV - 0.1757 \times RV^2 \quad \text{(litre/household/year)} \tag{28}$$

It should be noted, however, that R^2 of the regression is very low due to the unexplained factors that affect water consumption.

---

30 This utility function is a simplified version compared to the one discussed in Chapter III. In this case, latent propensity to switch to metering d^* is expressed as:

$$d^* = u(x^m(t),t) - T^m(x^m(t),t) - u(x^f(t),t) + T^f(t) \qquad \text{[from equation 25]}$$

Hence the propensity would be larger if: (1) T^m (hence metered price p) is smaller; (2) T^f is larger; or (3) x^f is smaller. Notice that (2) and (3) correspond to earlier Propositions 2 and 1, respectively.

31 We will use the word "tariff" to express a total (lump-sum) bill that a household is payable in a year.

32 We have argued, however, that the RV cannot directly affect water consumption. Here we are rather using the RV as a surrogate indicator for the income.

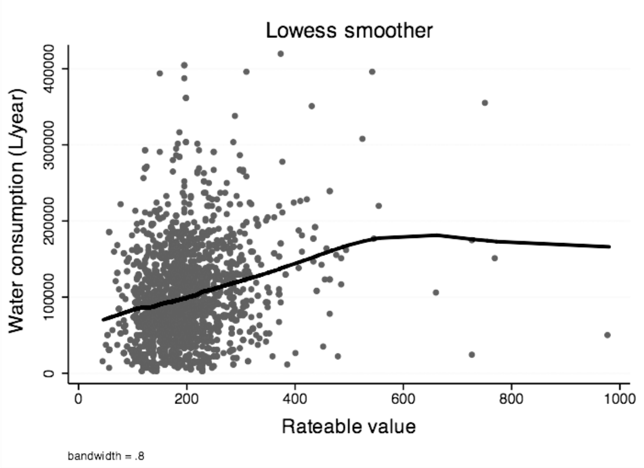

Fig.17 Water consumption (non-metered) against the RV with Lowess smoother

Table 11 Estimated OLS model for water consumption

	Model 6a (Non-metered only)		
Variables	Coefficients	Std. errors	
Constant	49860.58	8065.317	**
Rateable value (RV)	290.3771	66.55822	**
Rateable value squared	-0.1756794	0.1277138	
Sample size	1873		
R^2	0.0557		

Dependent variable: *water consumption* (L/year)
Heteroscadasticity-robust standard errors are shown.
* Significant (p<0.05); ** Strongly significant (p<0.01)

Second, Chapter V has estimated a relationship between the RV and the DEM:

$$D\hat{E}M = -0.0269 + \frac{27.94}{RV} \qquad \text{[from equation (22)]} \tag{29}$$

The corresponding volumetric effect of metering[33] is:

$$\Delta\hat{x} = \hat{x}^f \times D\hat{E}M = \hat{x}^f \left[-0.0269 + \frac{27.94}{RV} \right] \tag{30}$$

Inserting equation (28) into (30), we get:

$$\Delta\hat{x} = 6771.97 - 12.7203 \times RV + 4.7263 \times 10^{-3} \times RV^2 + \frac{1393104.61}{RV} \tag{31}$$

The metered water consumption x^m could be estimated as:

$$\hat{x}^m = \hat{x}^f - \Delta\hat{x} \tag{32}$$

Inserting equations (28) and (31) into (32), we have:

$$\hat{x}^m = 43088.61 + 303.10 \times RV - 0.1804 \times RV^2 - \frac{1393104.61}{RV} \tag{33}$$

33 It should be noted that this estimate of demand reduction does not consider possible price effects on water demand. However, we shall defer this argument to Chapter VII and **Appendix II**.

Third, current water tariffs[34] for the metered and the non-metered, levied by Anglian Water, are:

(Metered) $T^{m} = 67 + 0.0026943 \times x^{m}$ (£/year; x^{m} in litres) (34)

(Non-metered) $T^{f} = 310.64 + 0.6998 \times RV$ (£/year; RV in £) (35)

where: the constant terms indicate the standing charges that are levied irrespective of water uses or RV.

Fourth, we assume a constant returns-to-scale cost function for water:

$$TC = FC + w\,x \tag{36}$$

where: TC and FC are total and fixed costs for producing water, respectively, and

w, the marginal cost of producing water, is assumed to be constant.

In this case, average *variable* cost is equivalent to marginal cost. The total operating cost[35] of Anglian Water in 2008-2009 was £591.8 million/year (Anglian Water, 2009a: 48) whilst supplying 438 billion litres/year of water (Anglian Water, 2009b). Hence, marginal cost of water production is roughly estimated as:

$$w = 591.8\ (\text{million £/year}) / 438\ (\text{billion litre/year}) = 1.351 \times 10^{-3}\ (\text{£/litre}) \tag{37}$$

Fifth, the average incremental cost of installing and maintaining a water meter was estimated as 1.456×10^{-3} (£/litre) (Environment Agency, 2008b: 47). Hence we have:

$$m = 1.456 \times 10^{-3} \times x^{m} \quad (\text{£/household/year}) \tag{38}$$

Finally, we have an empirical model for the "first-best" metered tariff (equation 26):

$$\hat{T}^{m*} = T^{f} + m - w\Delta\hat{x} \quad (\text{£/household/year}) \tag{39}$$

Thus, inserting equations (31), (35), (37) and (38) into (39), we have:

$$\hat{T}^{m*} = 376.04 + 1.1583 \times RV - 2.6905 \times 10^{-4} \times RV^{2} - \frac{3910.44}{RV} \tag{40}$$

Assuming that the "standing charge" would remain the same as equation (34), we can deduce the **"first-best" volumetric charge *p**** that should raise the first-best tariff:

$$T^{m*} = 67 + p^{*} \times x^{m}$$

or $$p^{*} = \frac{T^{m*} - 67}{x^{m}} \quad (\text{£/litre}) \tag{41}$$

Thus, inserting equations (33) and (40) into (41), we have:

$$\hat{p}^{*} = \frac{309.04 + 1.1583 \times RV - 2.6905 \times 10^{-4} \times RV^{2} - 3910.44 / RV}{43088.61 + 303.10 \times RV - 0.1804 \times RV^{2} - 1393104.61 / RV} \tag{42}$$

b. Estimated results

Fig.18 shows predicted water consumptions for the non-metered before and after metering (from equations 28 and 33, respectively). The gap between them indicates that the DEM is predicted to be larger for smaller-RV households than larger-RV ones.

[34] This includes sewerage service charges for properties connected for foul water drainage only. For more information, see: http://www.anglianwater.co.uk/household/your-account/tariffs/standard-rates/ (accessed 1st July 2010).

[35] The "operating cost", according to the report of Anglian Water (2009a), may include both the fixed and variable costs. Therefore, although we provisionally use this cost as an approximation to the total variable cost, we need more detailed information on cost structures for more precise analyses.

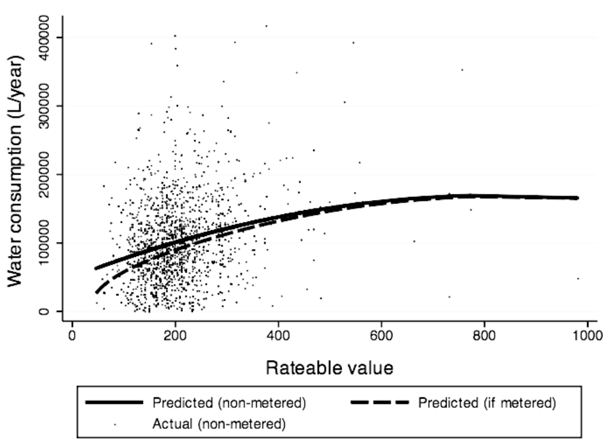

Fig.18 Predicted and actual water consumptions for non-metered households

Next, **Fig.19** shows the current non-metered tariff T^f that the households are actually paying (equation 35), and the metered tariff T^m that they will have to pay (after switching) under the current metered charges (equation 34), if they would consume water according to the prediction $\hat{x}^m$ (equation 33). It suggests that, under the current tariff scheme, "typical" households, which consume the predicted amounts of water, could enjoy tariff savings at all RV ranges.

Fig.19 also shows the "first-best" tariff T^{m*} (equation 40) that is expected to bring a socially efficient outcome. It shows T^f and T^{m*} are virtually the same at the low end of RV, but the gap between them widens as the RV increases. This implies the water company should impose higher tariff increases when higher-RV households switch to metering, because they would not show up enough benefits (i.e. DEM) for the water company to compensate metering costs.

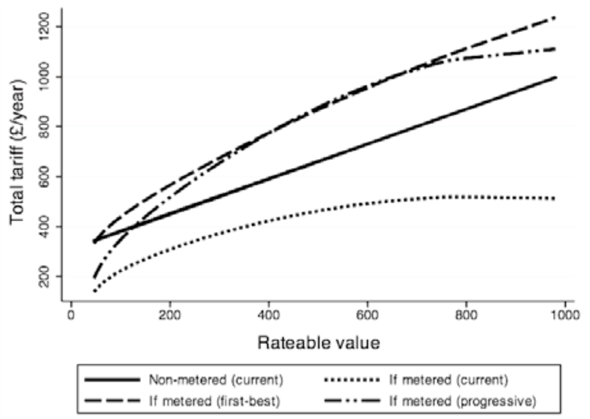

Fig.19 Estimated water tariffs against the RV for "typical" households (based on predicted water demands)

Fig.20 then shows the estimated "first-best" volumetric charge $\hat{p}^*$ (equation 42) that should raise, on average, the first-best tariff T^{m*}. The curve of p^* stays above the current charge at all ranges of RV, implying that the charge should be increased for all households if net metering costs are to be fully recovered. Moreover, it follows a convex pattern with a turning point around 350 of RV. The downward-sloping portion of p^* in the lower range of RV is attributed to lower water consumptions of lower-RV households (which makes the denominator of equation (41) very small relative to the numerator). Nevertheless, imposing higher volumetric charges on lower-RV households on such a ground would not be desirable as it effectively penalises their frugality in water consumption.

Therefore, we alternatively propose a "progressive" charge, which emulates the upward-sloping portion of p^* with the OLS regression, and then extrapolate it into the lower range of RV. Hence we conduct the OLS estimation of p^* on RV, where RV is restricted to over 350 (**Table 12**). Thus, we get the **progressive volumetric charge** $\boldsymbol{p_{pr}}$ (**Fig.20**):

$$p_{pr} = 0.0047 + 1.638 \times 10^{-6} \times RV \qquad (\text{£/litre}) \tag{43}$$

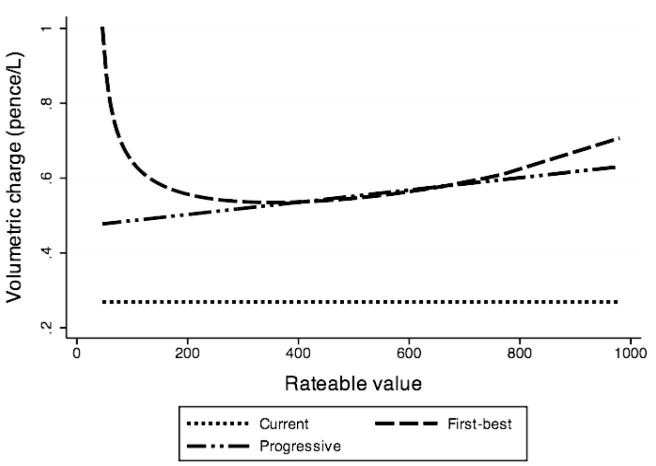

Fig.20 Current and proposed metered volumetric charges against the RV

Table 12 Estimated OLS model for the progressive charge

	Model 6b (households with RV>350 only)		
Variables	Coefficients	Std. errors	
Constant	0.4700092	0.0024944	**
Rateable value (RV)	0.0001638	0.00000553	**
Sample size	218		
Adjusted R^2	0.8019		

Dependent variable: *p* (the "first-best" volumetric charge)* (pence/L)
* Significant (p<0.05); ** Strongly significant (p<0.01)

We may then deduce the "progressive" tariff T_{pr}^{m} that would be collected, on average, under the progressive charge:

$$T_{pr}^{m} = 67 + p_{pr} \times x^{m} \tag{44}$$

Inserting equations (33) and (43) into (44), we get:

$$\hat{T}_{pr}^{m} = 267.24 + 1.4952 \times RV - 3.5140 \times 10^{-4} \times RV^{2} - 2.9550 \times 10^{-7} \times RV^{3} - \frac{6547.6}{RV} \tag{45}$$

Fig.19 shows the "progressive" tariff (equation 45) would reduce financial burdens especially for households in the lower range of RV, relative to the "first-best".

In summary, although the progressive charge (equation 43) is deemed socially less efficient than the "first-best" charge (as it departs from the "first-best" solution of equation 42), it would be more desirable (relative to either the "first-best" or the current charge) in the following points:

- The equation (43) is simpler than the first-best charge (equation 42). This will make the progressive charge easier for customers to understand.
- It encourages lower-RV households to switch to metering through reducing their tariffs, relative to the first-best. This is important because they constitute a bulk of the remaining non-metered households (**Fig.17**), and hence switching them to metered status will generate a large magnitude of DEM, which is favourable from the environmental viewpoint.
- It could encourage higher-RV households to save more water by imposing them progressively higher volumetric charges, compared to the current charge.
- It would be justifiable, from the viewpoint of social equity, to subsidise lower-RV households for the metering costs in this way, whilst requiring higher-RV ones to pay back fully the net metering costs.

- In spite of the above, required amounts of such subsidies would be much smaller than the current tariff, as the progressive tariff is much closer to the first-best tariff (which is financially neutral) than the current tariff (**Fig.19**).

Having discussed “average” consequences of different charging schemes, we may now ask what the actual implications of those schemes are for each non-metered household. We examine this by inserting actual water consumptions of the non-metered, x^f, instead of the predicted ones, into equations (30) and (32), and calculating the tariffs accordingly.

The results are shown in **Fig.21**. Under the current tariff (**Fig.21(a)**), the majority of households are able to save expenditure for water by switching (as most dots are below the solid line). By contrast, under the first-best tariff (**Fig.21(b)**), the plots are more dispersed in an upward direction, implying the increasing financial burdens on households at all RV ranges. In particular, those households consuming a lot of water are heavily penalised under this scheme. The progressive tariff (**Fig.21(c)**) then has an effect of “compressing” the dots downwards at the lower range of RV, lightening their financial burdens.

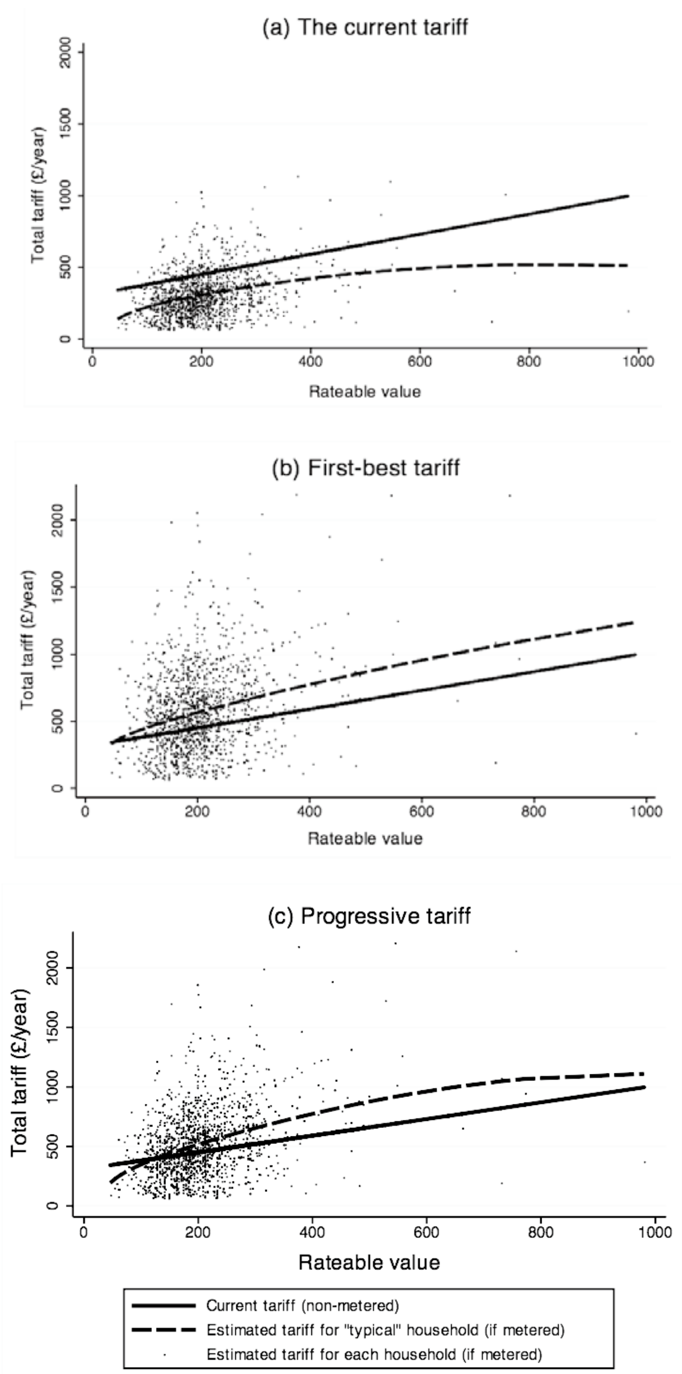

Fig.21 Estimated tariffs for “typical” and each household

3 Summary

This chapter initially formulated the "first-best" tariff that would achieve a socially efficient outcome that was financially neutral as well. Then, its adjusted version, or the "progressive" tariff, was proposed, which would reduce financial burdens of lower-RV households.

Although the analyses of this chapter have been focused on proposing an alternative *metered* tariff structure for enhancing social efficiency, the same objective might instead be achieved by adjusting the *non-metered* tariff, or both the metered and non-metered tariffs. This is because the non-metered tariff is not exogenous but set by the same water company in conjunction with the metered tariff. Investigation into this issue is left to future studies.

VII Conclusion

This study is aimed at quantifying magnitudes of water saving that might be achieved through water metering (i.e. the demand effect of metering, or DEM), and appraising the relevant social welfare. We focus our attention on situations in East Anglia region in England, where water supply is tightly regulated and water metering is largely optional. Chapter III therefore begins by establishing a theoretical framework suitable to such situations, on the basis of microeconomic consumer theories. Hence it is theoretically demonstrated that: the less water the household consumes when flat-charged, or the larger the rateable value of a household, the more likely they opt for water metering; there exists a positive DEM (in the absolute value term); and the larger the rateable value of a household, the smaller the DEM (given the household do switch to metering).

The above theory is duly tested in Chapters IV and V with econometric analyses using cross-sectional and panel data of households provided by Anglian Water. The theory nonetheless suggests the endogeneity problem in estimating the DEM correctly: the metering dummy variable is deemed endogenous in estimating water consumption, thereby rendering the ordinary least square estimators inconsistent. The analyses are therefore extended to treatment-effects and panel data models, which might overcome the problem. Consequently, using the fixed-effects model with panel data, the DEM is successfully estimated as 13.2% on average with a narrow 95% confidence interval. Moreover, an adjusted version of the model predicts more accurately an inverse relationship between the DEM and the rateable value, which is subsequently exploited in Chapter VI.

Chapter VI discusses social welfare of metering, which offers a policy implication: whereas the current tariff somehow subsidises the metering costs, the socially efficient outcome could be achieved by making the tariff financially neutral with respect to metering costs and benefits. This would enable the water company to undertake alternative investments, for instance, in repairing more water pipes to reduce leakages (instead of subsidising metering costs). Hence the "first-best" tariff is formulated, which is financially neutral on average. Nevertheless, it will put heavier financial burdens on most households through tariff increases. Therefore, an alternative "progressive" tariff is proposed, which could ease financial burdens for poorer households, yet is closer to the financially neutral position than the current tariff. It is therefore advised that, when volumetric charges are to be increased in the future, the progressive charge would be considered.

On the other hand, the proposed tariff model warrants some qualifications, and hence suggests directions for future research. First, we are actually far from the ideal "complete information" condition in respect to water demands, when the water company knows only rateable values. For instance, the proposed tariff could levy disproportionately heavier burdens on households with higher occupancy – most typically with a lot of children. However, such an issue could be dealt with by issuing them childcare subsidies. We would rather insist that any tariff scheme should be sufficiently simple to administer, focusing on as little information as possible; the remaining social concerns could then be dealt with by other tax credits or subsidies. This is partly because it will give a simpler charging scheme that is easier for customers to understand, and because the water company could save indirect costs of gathering necessary information. Having said that, future research should seek for better household indicators than the rateable value for establishing socially efficient tariff schemes.

Second, we did not model the effect of price changes on the DEM. Modelling it requires the price elasticity (as well as income elasticity) of demand for water. The results of previous studies on this subject, mainly from USA and mainland Europe, have varied widely except that most studies indicated water demands were price inelastic (Arbués et al., 2003).

Although few studies have estimated the price elasticity in UK, **Appendix II** of this study envisages finding possible ramifications of price effects on demand by assuming a price elasticity of 0.35 after Dalhuisen et al. (2003). Preliminary results obtained therein reinforce the earlier conclusion of this chapter: the progressive tariff would be socially more efficient than the current tariff.

Third, we did not include external environmental costs in the water production cost. Nevertheless, such environmental costs are thought to become increasingly significant as water abstraction is approaching or possibly exceeding the environmental capacity in East Anglia region (Environment Agency, 2008a: 15). Thus, we may need substantial inputs from natural sciences to advance research in this direction, as environmental impacts of water abstractions (and subsequent discharges from sewage treatment works) could be very complex.

Appendix I: Mathematical analyses for Chapter III

This appendix aims to provide mathematical solutions to the household's decision problem discussed in Chapter III, using a parametric model and the constrained optimisation technique. Most of the materials in Sections 1 and 2 are drawn from Kyle (2009). We then extend the analyses in Section 3 to prove Proposition 3.

Most of the notations used in Section III-1 are carried over here. So let:

x_1 be quantity of water consumed,
x_2 be quantity of numeraire consumed (with a price normalised as one),
p be a price of water when meter-charged,
f be a water charge when flat-charged on the basis of rateable values,
m be an income of a household,
c be a satiation point of water consumption,
and
X_m: (x_1^m, x_2^m) be the optimal consumption bundle when meter-charged,
X_f: (x_1^f, x_2^f) be the optimal consumption bundle when flat-charged,
$U_m(X_m)$ be the maximum utility obtainable when meter-charged,
$U_f(X_f)$ be the maximum utility obtainable when flat-charged,
DEM be the demand effect of water metering.

1 Proof of Propositions 1 and 2

We assume that the household's utility could be expressed as:

$$U(x_1,x_2) = x_2 - (c - x_1)^{\alpha} \quad \text{(where } \alpha>1) \qquad \text{if } x_1 < c$$
$$= x_2 \qquad \text{if } x_1 \geq c \tag{46}$$

Function (46) satisfies the assumptions we made in Section III-1-a.

First, X_f has already been obtained by graphical analyses in Section III-1-c as:

$$X_f : (x_1^f, x_2^f) = (c, m - f) \tag{47}$$

Hence, by equation (46), we have:

$$U_f = m - f \tag{48}$$

Next, we turn to obtain X_m and U_m using the constrained optimisation technique. Since the slope of the budget constraint B_m is negative, it must have a tangency point with the indifference curve at the strictly convex segment (i.e. where $x_1<c$).

Hence household's objective is to:

$$\underset{x_1, x_2}{Max} \quad U = x_2 - (c - x_1)^{\alpha}$$

$$\text{subject to} \quad p x_1 + x_2 \leq m \tag{49}$$

Hence we write the Lagrangean:

$$L = x_2 - (c - x_1)^{\alpha} + \lambda(m - px_1 - x_2) \tag{50}$$

The first-order necessary conditions for the maximum are:

$$\frac{\partial L}{\partial x_1} = -\alpha(c - x_1)^{\alpha-1}(-1) + \lambda(-p) = 0 \tag{51}$$

$$\frac{\partial L}{\partial x_2} = 1 - \lambda = 0 \tag{52}$$

$$\frac{\partial L}{\partial \lambda} = m - px_1 - x_2 = 0 \tag{53}$$

From equation (52),

$$\lambda = 1 \tag{54}$$

Inserting equation (54) into (51),

$$\alpha(c - x_1)^{\alpha-1} = p$$

$$\Leftrightarrow \quad c - x_1 = \left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}}$$

$$\Leftrightarrow \quad x_1^m = c - \left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} \tag{55}$$

Inserting equation (55) into (53),

$$x_2^m = m - pc + p\left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} \tag{56}$$

Hence we have:

$$X_m : (x_1^m, x_2^m) = \left(c - \left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}}, \quad m - pc + p\left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} \right) \tag{57}$$

Inserting equation (57) into (46), we get:

$$U_m = \left[m - pc + p\left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} \right] - \left[c - \left(c - \left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} \right) \right]^{\alpha}$$

$$\Leftrightarrow \quad U_m = m - pc + p\left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} - \left(\frac{p}{\alpha}\right)^{\frac{\alpha}{\alpha-1}} \tag{58}$$

We must have non-negative water consumption at the optimum x_1^m, hence:

$$x_1^m = c - \left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} > 0$$

or

$$c > \left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} \tag{59}$$

We have hypothesised in Section III-1-c that: the household will opt for metering if $U_m > U_f$. From equations (48) and (58), therefore, the household will opt for metering if:

$$m - pc + p\left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} - \left(\frac{p}{\alpha}\right)^{\frac{\alpha}{\alpha-1}} > m - f$$

or

$$f > pc - p\left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} + \left(\frac{p}{\alpha}\right)^{\frac{\alpha}{\alpha-1}} \tag{60}$$

subject to $c > \left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}}$ [by equation 59]

Following equation (60), we may now think of another parameter d^* that indicates latent propensity to opt for metering:

$$d^* = U_m - U_f = f - pc + p\left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} - \left(\frac{p}{\alpha}\right)^{\frac{\alpha}{\alpha-1}} \tag{61}$$

The above discussions suggest that, when d^* is positive, the household would opt for metering.

Partially differentiating equation (61), we have,

$$\frac{\partial d^*}{\partial c} = -p < 0 \tag{62}$$

$$\frac{\partial d^*}{\partial f} = 1 > 0 \tag{63}$$

From equations (62) and (63), we could endorse our earlier propositions:

- The smaller the c, the more likely the household opts for metering, holding f constant, and taking m and p as given. (**Proposition 1**)
- The larger the f, the more likely the household opts for metering, holding c constant, and taking m and p as given. (**Proposition 2**)

2 Proof of the existence of the DEM

From the optimal water consumptions, we can derive the demand effect of metering as:

$$DEM = \left|x_1^m - x_1^f\right| = x_1^f - x_1^m$$

$$= c - \left[c - \left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}}\right]$$ [by equations 47 and 55]

$$= \left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}} > 0 \tag{64}$$

Partially differentiating this with respect to p, we have:

$$\frac{\partial(DEM)}{\partial p} = \frac{1}{\alpha-1}\left(\frac{p}{\alpha}\right)^{\frac{-\alpha}{\alpha-1}}\left(\frac{1}{\alpha}\right) > 0 \tag{65}$$

Thus, this model also reveals the existence of a positive DEM (in the absolute value term) and a positive relationship between p and the DEM. That is, the higher the p, the larger the DEM we could expect once the household switches to metering (subject to equation (59)).

3 Proof of Proposition 3

In deriving Proposition 3 (Section III-1-g), we assumed that the indifference curves get steeper as we move up the two-good plane. In our parametric model, this can be expressed as an increase in α when m gets larger, because larger α gives steeper indifference curves (**Fig.22**).

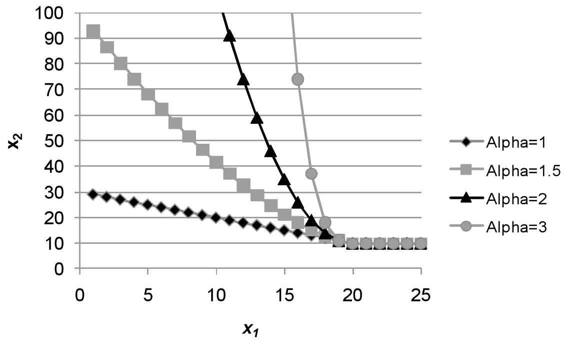

Fig.22 Simulated indifference curves with different α
(Conditions: $x_1^f = c = 20$; $x_2^f = m - f = 10$)

Therefore, we may well model that: α increases in proportion to m, which in turn increases in proportion to f. If we assume simple linear relationships among them, we have:

$$\alpha = g \times m = g \times (h \times f) = k \times f \tag{66}$$

where: g, h, and k ($\equiv gh$) are positive constants.

Thus, from equations (64) and (66), we have:

$$\frac{\partial(DEM)}{\partial f} = k\left[\frac{\partial(DEM)}{\partial \alpha}\right] = k\left(\frac{p}{\alpha}\right)^{\frac{1}{\alpha-1}}\left[-\frac{\ln\left(\frac{p}{\alpha}\right)}{(\alpha-1)^2} - \frac{1}{(\alpha-1)\alpha}\right] \tag{67}$$

This derivative is definitely negative, subject to $p>\alpha$. That is, the larger the f, the larger the α (i.e. the steeper the indifference curve) (by equation 66), and hence the smaller the DEM (by equation 67). (An example of simulated relationships is given in **Fig.23**) This endorses Proposition 3, subject to the given assumptions.

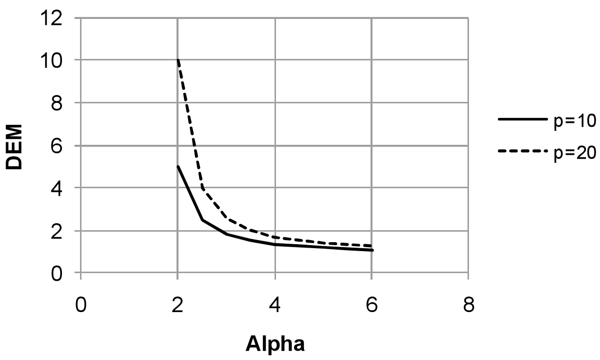

Fig.23 Simulated relationship between α and the DEM

Appendix II: Social welfare of water metering where the demand is dependent on water prices

Throughout Chapter VI, we assumed for simplicity that the demand effect of metering is constant regardless of volumetric water charges. This appendix aims to generalise those discussions by allowing the demand to change in response to the price change, and explore ramifications on social welfare of water metering.

1 Modelling framework

In Chapter VI, we obtained the "first-best" (financially-neutral) tariff and hence volumetric charge (or price) for water, according to the sequences shown in **Fig.24**. Those sequences were quite straightforward, since the water demand was assumed to be independent of price. Thus, we obtained the "first-best" price:

$$p^* = \frac{T^{m^*} - 67}{x^m} \tag{41}$$

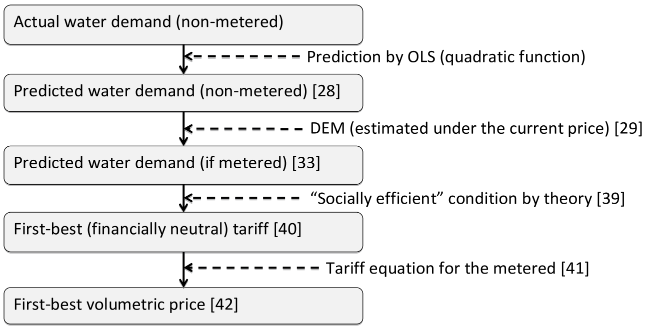

Fig.24 Derivation of the "first-best" water tariff with no price effects on demand
Note: The numbers in square brackets indicate relevant equations.

By contrast, we now allow the demand to depend on the price. In this case, we may well hypothesise that the demand undergoes two-step reductions as shown in **Fig.25**. The first step is the same as Chapter VI: the household is installed with a meter, and charged the current volumetric price. For this step, we already have an empirical estimate of demand reduction, which is the DEM (equation 29). Hence we get a predicted water demand if household is metered and charged the current price (equation 33). Then, as the second step, the household faces a price increase from the current price to a new "socially-efficient" price to be obtained subsequently. Accordingly, the demand will be further reduced in this step as:

(% reduction in demand) = (price elasticity of demand) × (% increase in price)

On the basis of this newly obtained demand, the "socially-efficient" tariff and hence the "socially-efficient" price[36] could be calculated as before. Nevertheless, in contrast to Chapter VI, the demand (and hence the tariff) is now endogenous (i.e. dependent on price). Such endogeneity is indicated by an upward pointing arrow on the right of **Fig.25**.

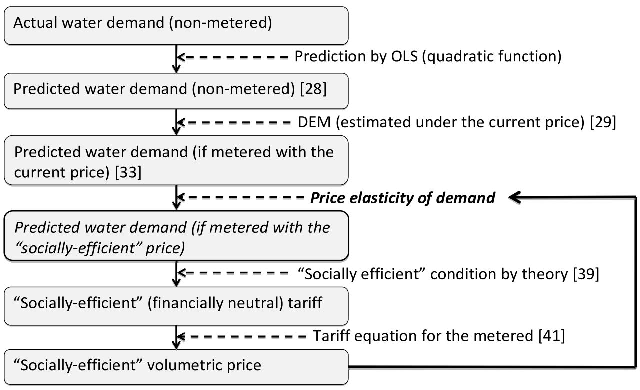

Fig.25 Derivation of the socially-efficient water tariff with price effects on demand
Note: The numbers in square brackets indicate relevant equations.

Thus, we can succinctly write a price equation as:

$$p^* = \frac{T^{m^*}(p^*) - 67}{x^m(p^*)} \tag{68}$$

This is a modified form of equation (41) above, expressing that the socially efficient tariff T^{m^*} and the water demand x^m are now dependent on the socially efficient price p^*. This would make the derivation of the socially efficient price mathematically involved, since we now need to solve a nonlinear equation. Therefore, we alternatively simplify arguments by taking for granted the "first-best" and "progressive" prices previously obtained in Chapter VI, as the first approximations

[36] We will not term these as the "first-best" to avoid confusion with those obtained in Chapter VI.

towards the socially efficient solution implied by equation (68). We then explore ramifications by considering relevant price effects on demand. Such a modified approach is depicted in **Fig.26**. Here the prices are given *exogenously* according to the results of Chapter VI.

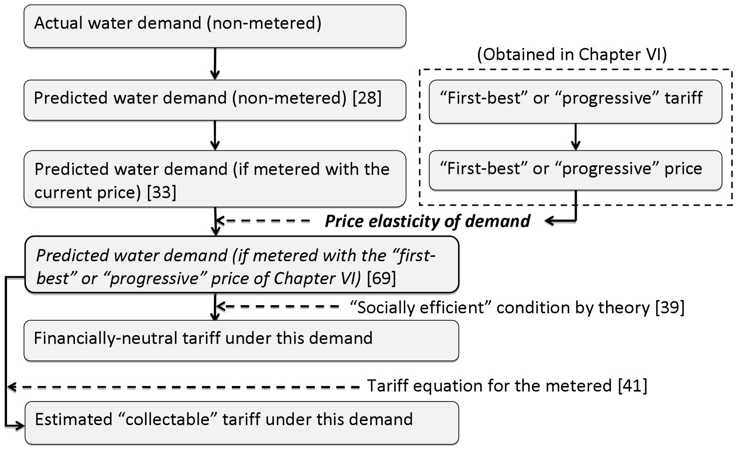

Fig.26 Simplified procedures for investigating price effects on demand
Note: The numbers in square brackets indicate relevant equations.

We now assume that the price elasticity of water demand would be 0.35, which is the median value of previous studies according to Dalhuisen et al. (2003: 295). Thus, water demands under the new prices are estimated as:

$$x^m = \left[1 - 0.35 \times \frac{(p - p_c)}{p_c}\right] \times x_c^m \tag{69}$$

where: p is the new (i.e. "first-best" or "progressive") prices,
p_c is the current volumetric price (before price increase),
x^m is the water demand under the new prices,
x_c^m is the water demand under the current price,
0.35 is the assumed price elasticity of demand.

Taking the above demand as given, we are now able to calculate two estimates for tariffs: the financially neutral (hence socially efficient) tariff, T^{m*} (equation 70), and the tariff that is collectable on average, $T^m_{collectable}$ (equation 71), as follows:

$$T^{m*} = T^f + m - w\Delta x \qquad \text{[from equation 39]}$$

Inserting equations (32) and (38) into this:

$$T^{m*} = T^f + 1.456 \times 10^{-3} \times x^m - w(x^f - x^m) \tag{70}$$

$$T^m_{collectable} = 67 + p \times x^m \qquad \text{[from equation 41]} \tag{71}$$

These two tariffs would be identical in a case of any possible solution to equation (68). In other cases, however, there is a gap between the two, as we will see in the next section. The larger the gap, the more subsidies the water company must spend on metering costs. Hence smaller gaps would be more desirable from a viewpoint of social efficiency.

2 Estimated results

Fig.27 shows predicted water consumptions (demands) when we have price effects on demand. As a benchmark, the first and second thin lines reproduce the previous predictions in Chapter VI (**Fig.18**) where we have no price effects. Then, the third and fourth thick lines show the reduced demands in response to the relevant price increases (equation 69). The demand reduction induced by imposing the "first-best" price of Chapter VI would be very severe especially for the lower-RV households, as their demands are reduced to near zero as a result of very high prices imposed on them (**Fig.20**).

This is clearly a socially undesirable situation, and hence we drop this case from the subsequent discussions.

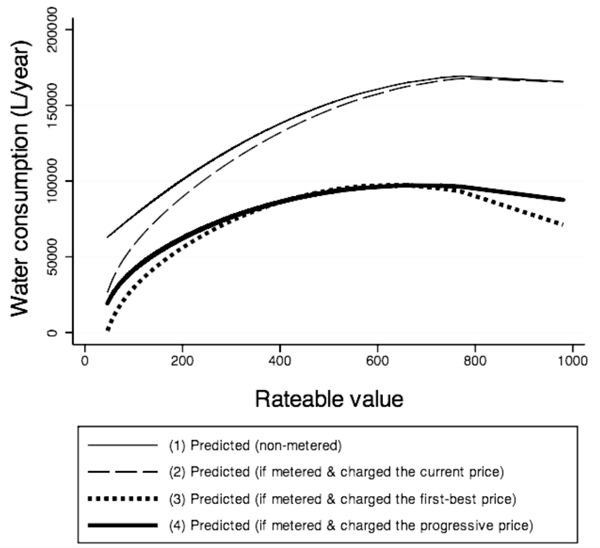

Fig.27 Predicted water consumptions with or without price effects on demand

On the other hand, when we alternatively impose the “progressive” price of Chapter VI, the demand reductions of lower-RV households due to the price increase (i.e. the gap between lines (2) and (4)) are kept minimal, whereas those of higher-RV households are considerable thanks to their initially larger water demands, and to the higher price increases imposed on them under the progressive charging (**Fig.20**)[37].

Fig.28 then depicts estimated tariffs, where we have price effects on demand and the household faces a price increase from the current to the “progressive” price of Chapter VI. As benchmark cases, the thin lines (1) to (3) reproduce the tariffs obtained in Chapter VI where we had no price effects. To recap, the line (1) is a tariff for the non-metered under the current tariff schedule for them (equation 35); the line (2) is a metered tariff that is collectable on average under the current price (equation 34); and the line (3) is the socially efficient (financially neutral) tariff when we have no price effect – i.e. the “first-best” tariff of Chapter VI (equation 40).

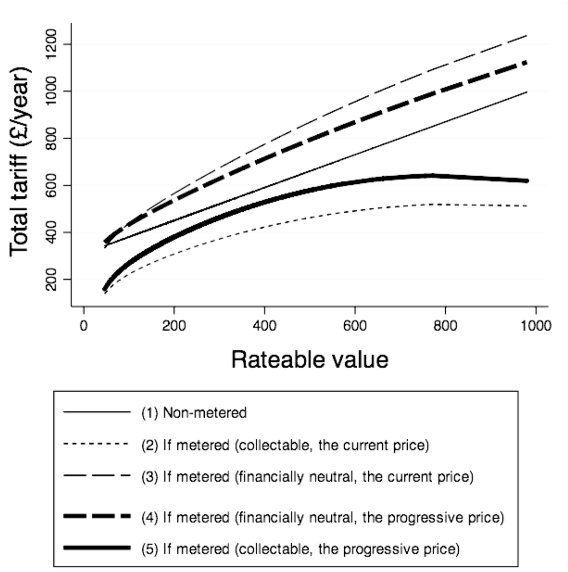

Fig.28 Effects of a price increase (from the current to the “progressive”) on tariffs

[37] However, we should be mindful that their demand reductions due to price increases might actually be smaller, because we have argued that the water demand of wealthier households are more *inelastic* than that of poorer ones (see **Fig.7**). But we will abstract from this fact here, and stick to the uniform price elasticity of 0.35 regardless of incomes.

Next, the thick lines (4) and (5) indicate the two kinds of tariffs that are shown in the two lowermost boxes of **Fig.26**. The line (4) indicates the socially efficient (financially neutral) tariff when the demand is reduced in response to the price increase. This line is slightly shifted downwards relative to the line (3), because the water company could now enjoy larger benefits from water savings (i.e. demand reductions). This point is apparent in equation (70): the smaller the x^m (demands after price increase), the lower the T^{m*} (socially efficient tariff under such a condition) should be.

Meanwhile, the line (5) indicates a tariff that is collectable on average when the price is increased and the demand is reduced in response. The line (5) shifts upwards in comparison to the line (2), which is our reference case. According to the tariff equation (41), the reduction in demand reduces the tariff that a household is payable (i.e. the collectable tariff), whereas the increase in price increases the same. Therefore, the upward shift of the line (5) suggests that the latter effect dominates the former for every household. Nonetheless, such a shift is kept minimal for the lower-RV households. Thus, in comparison to the reference case, the progressive tariff would contribute to augmenting a revenue base of the water company, whilst circumventing too much financial burdens on poorer households.

Having observed the effects of price increase, the key issue here is the gap between the socially efficient (financially neutral) tariff and the collectable tariff: the narrower the gap, the more socially efficient the relevant charging scheme would be. To begin with, our reference case is the current price. Under this price, we do not have to consider the price effect (but the DEM only). Hence, the socially efficient tariff is the line (3), whilst the collectable tariff is the line (2). On the other hand, after the price increase, the socially efficient tariff is the line (4), whilst the collectable tariff is the line (5), as we have discussed.

From **Fig.28**, it is obvious that the gap between the lines (4) and (5) is generally narrower than that between the lines (3) and (2). We could therefore claim that the "progressive" tariff is closer to the socially efficient position than the current tariff. Thus, we may have found a further justification to recommend the "progressive" tariff in favour of the current tariff, from a viewpoint of social efficiency.

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英国イースト・アングリア地域における水道メーターの導入と水需要・社会福祉

上田達己，MOFFATT Peter

要　旨

近年英国では，将来の水資源の逼迫への懸念から，水需要を節減させる効果をもつ水道メーターの設置（すなわち従量式の水道料金制度の導入）が推進されている。本論文は，英国東部のイースト・アングリア地域を事例として，水道メーターの導入が，一般家庭の水需要および社会福祉に与える影響を明らかにすることを目的とする。

第 1・2 章は，研究の背景・目的を述べるとともに，既往研究のレビューに基づき研究課題を特定する。

第 3 章は，ミクロ消費者理論にもとづいて，水道メーターの導入と家庭の水需要の関係性を理論的に考察する。前提条件として，当該地域の現況に基づき，当初各家庭は固定料金（各家庭の不動産価格に比例した料金）を支払っており，水道メーターの設置（従量料金制度への乗換え）は任意であるとする。これら前提のもと，以下の 3 つの命題が理論的に導かれる。①ある家庭の水需要の飽和点（固定料金下（水の限界費用がゼロの時）の水需要量）が小さければ小さいほど，その家庭は，従量料金制度に乗り換えるインセンティブが高い。②ある家庭の不動産価格が高ければ高いほど，その家庭は，従量料金制度に乗り換えるインセンティブが高い。③ある家庭の不動産価格が高ければ高いほど，その家庭が示す DEM（Demand Effect of Metering：水道メーター導入のもたらす水需要削減効果）は小さい。

第 4 章は，当該地域の主要な水供給公社である Anglian Water の提供する交差系列データを用いた多重回帰分析等を行い，前章の命題を計量経済学的に実証する。ところが，命題①により，交差系列データを用いた多重回帰モデルにおいては，推定された DEM に偏りがあることが示唆される（内部性の問題）。実際，メーター設置ダミー変数を内生変数とした同時方程式モデルによる検討から，多重回帰モデルは DEM を過大評価する傾向があることが明らかとなる。

そこで，第 5 章は，パネル（交差時系列）データを用いた回帰分析を行い，内部性の問題を解決する。結果として，平均 13% の DEM が観察される。（すなわち，水道メーターの設置は，家庭の水需要を平均 13% 減少させることが推定される。）さらに，メーター設置ダミー変数と不動産価格の比を説明変数に加えることによって，家庭の不動産価格と DEM の間の反比例の関係（命題③）を実証する。

第 6 章は，厚生経済学理論に基づき，社会的にみて効率的な料金制度のあり方を論じる。前提条件として，水供給側が各世帯の水需要関数を把握しているとし（完全情報の仮定），ここでは，前章で実証した命題③を援用する。結果として，社会的にみて効率的な料金は，水道メーター設置の純費用（＝粗費用－設置の社会的便益）を，従量料金の値上げによって補填するような（予算中立的な）料金体系であることが理論的に推察される。ここで，メーター設置の社会的便益は，DEM による水供給費用の節減であると把握される。したがって，命題③により，高所得の（高い不動産価格の住宅を持つ）世帯ほど，メーター設置の社会的便益（DEM）が小さい（すなわち設置の純費用が大きい）ので，そのような世帯に対しては，従量料金を高く設定することが望ましいと推論される。さらに，前章までの実証分析結果に基づき，そのような特性をもつ累進的な従量料金制度を具体的に提案する。

第 7 章は，研究の総括を行うとともに，今後の研究の方向について論じる。

本論文の成果は，水道料金のみならず，農業用水等の料金制度と水需要を考察するうえでも有用な情報を提供する。とりわけ，以下のような事例（条件下）に適用することが最も有用であると考えられる。①水需給が逼迫しており，水需要の削減が大きな社会的便益を生み出すこと。②従量料金制度への乗換えが任意であること。③水需要削減のインセンティブが各々の需要者によって異なり，その差異を水供給側が定量的に把握できること。

キーワード：上水道，水道メーター，水需要，計量経済学，社会福祉