Quantity Uncertainty and Demand: The Case of Water Smart Reader Ownership

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Abstract:

There are a number of instances when consumers have imperfect information regarding the quantity they consume. This paper has two objectives: (1) to formally describe how quantity uncertainty is likely to affect consumer behavior; and (2) to describe how these changes in behavior are likely to differ depending on how the quantity uncertain good is priced. We develop a theoretical model of consumer behavior under quantity uncertainty which we use to illustrate how different price structures and different locations within price structures matter for how information impacts behavior. We test these hypotheses using a unique panel data set containing information on water consumption habits of more than 88,000 households in the City of Aurora, Colorado. In 2005, Aurora subsidized the purchase of electronic devices for households to monitor water use. These devices provide households with real time information on their water use. We find that, consistent with the aims of the program, households with the device decreased their water use during periods when they faced a constant marginal price; however, contrary to the aims of the program, their consumption increased during periods when they faced an increasing block rate pricing structure. These results are consistent with the predictions of the theoretical model developed herein.

I. Introduction

Many economic decisions are characterized by uncertainty. Over the years, significant effort has been put into developing a better understanding of the effects of uncertainty on consumer behavior.[1] Whereas numerous studies have considered uncertainty as it relates to prices or the quality of goods, few have analyzed the impacts of uncertainty as it relates to the *quantity consumed*.[2] Despite this, there are a number of instances in which consumers have imperfect information about the quantity they consume. In many cases, this uncertainty goes hand-in-hand with pricing structures that penalize consumers for excessive consumption such as an increasing block rate structure[3] commonly used in water and a penalty for use of cell phones over the plan allocation.[4].

In each of these cases, "quantity uncertain" consumers may have an idea (biased or unbiased) based on past experience about how much they are consuming, but the actual amount consumed is unknown at the time of use *and* only revealed post consumption. Quantity uncertainty likely manifests itself in two ways. First, because households are unable to monitor their consumption, they may consume more or less than they had hoped over the course of the bill period. Second households may develop biased

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[1] For a comprehensive review of the early literature see Machina 1987.

[2] Although one may think of a mapping between quality and quantity, we draw a distinction from this literature in that the consumer does not know how much they will be billed for consumption. This is in stark contrast to the quality literature where, quality and, hence, utility derived from the good is unknown. Here, we assume that utility for the good is known, although residual income and therefore utility from a numeraire good is unknown at the time of purchase.

[3] Increasing block rate structures are characterized by different marginal prices for different levels of consumption. For example, a two tiered increasing block rate structure may charge households $2 for each thousand gallons below 10,000 and $4 for each thousand gallons above 10,000. The main idea being that the marginal prices are increasing as one increases consumption.

[4] Cell phone usage is a little different than the commodity considered here, water, in that customers may tailor their plan according to needs where as most households have a fixed water service provider. Further, the penalties imposed for consuming beyond a plan are larger relative to income. For example, one provider charges $0.40 for each additional minute consumed, which can quickly add up. As we will see, the larger is the price difference between consumption blocks, the greater the consumer will "cut back" to avoid this penalty.

beliefs about their actual water use due to the relative costliness of monitoring actual consumption across bill periods[5].

In recent years, creating "smart" consumers, by reducing quantity uncertainty, has become an increasingly popular goal among utilities. Google's PowerMeter program is an example of such a program designed to inform households about electricity consumption. Participating households are provided real-time home energy information on their computer. The idea being that "smart" consumers will use less electricity. As Google states, "Giving people access to better information about their energy use is essential to achieving smarter and more efficient use of energy." Programs such as these that tout that if only consumers had information about their consumption they would obviously cut back on consumption.

Of interest is how uncertainty of this type enters into the consumer's decision process and to what extent it reducing it impacts behavior. In this study we develop a model of consumer behavior under uncertainty that captures both the risk associated with over/under consuming, and the possibility that consumers have biased expectations about their use. This model is used to develop predictions as to how consumers are likely to change their behavior as they become more or less quantity uncertain and to what extent these changes in behavior are conditional on the type of price structure they face. Specifically, we consider two different types of pricing structures: constant marginal price and increasing block rate. These predictions are tested empirically, testing the responsiveness of households to increased quantity information regarding their water use.

[5] Jordan (1999) provides examples of how, even with water bill in front of consumers, it might be difficult to identify how much water a household has consumed.

When consumers face a constant marginal price, our model predicts that, abstracting from the potential effects of eliminating bias, the impact of reducing quantity uncertainty largely depends on the consumer's preferences toward risk. Risk averse, consumers will consume more, while risk neutral consumers will not change their behavior.

By contrast, when facing an increasing block rate structure, the effect quantity uncertainty has on consumption is not solely a function of the consumer's preferences towards risk; rather it also depends on where the consumer was located within the block rate structure prior to receiving information. The block rate structure, by itself, is likely to induce behavioral responses that are consistent with less or greater "risk aversion" than is present in preferences alone depending on the location of the consumer within the rate structure For example, when facing penalty rate structures risk neutral consumers are likely to respond to a reduction in uncertainty in a way that makes them appear as if they are risk averse (when below the threshold) or risk loving (when above the threshold).

The effect of information will either be muted or exacerbated depending on the presence of biased expectations about water use. As has been pointed out in the Google Powermeter program, households underestimate there electricity consumption. This has been discussed by water utility managers as well. Hence, if households are given information about water consumption they will decrease their consumption. This is not due to risk aversion but that households underestimate how much each individual application of water uses. If this is the case the movement in consumption from information may have two forces that move in opposite directions, one from the push downward of reducing the bias that households have about consumption and a push

upward through a reduction in "risk aversion." When "penalty pricing" structures (e.g. increasing block rate pricing structures) are in place this can result from both a reduction in the curvature of the utility function and a reduction in "risk" from not having to worry about being penalized for "excess" consumption (e.g. jumping over block boundaries and incurring a higher marginal price for consumption). It becomes an empirical question as to whether the reduction in bias wins out over the impact of information combined with the muting of the effects of the price structure.

Empirical tests of the hypotheses generated by the theoretical model are made using the consumption data of over 88,000 residential water customers in Aurora, Colorado over the period 2000 to 2005. In 2005, Aurora water began providing rebates to households to purchase a Water Smart Reader (WSR). WSR's are small devices that can be placed on one's refrigerator and receive information on water use wirelessly from the water meter. Without a WSR, or similar device, real time information on water use may be difficult to acquire or is not readily available. As a result, households are unlikely to know, before they receive the bill, how much they have consumed during the bill period (Jordan 1999).

WSR devices allow households to easily monitor instantaneous, as well as cumulative, water use.[6] Our data set includes customers who participated in the program and those who did not; both before and after the devices were made available. Moreover, we observe both groups during periods when water was priced according to an increasing

[6] For households in our sample, prior to 2005, there was no, legal way to easily acquire such information as meters are buried underground and not accessible.

block rate pricing (IBR) structure[7], as well as, during periods when households faced a constant marginal price.

We find that those households with a WSR *decreased* water use in periods of constant pricing consistent with the belief that households typically underestimate their water use. However, contrary to the original intent of the program, we find that households owning a WSR (relative to non-WSR owning households and WSR household use prior to receiving the device) during periods where water is priced according to an IBR. The latter, while consistent with our theoretical model, is not consistent with the objectives of the policy and the informal expectations in the literature that information will induce conservation.[8] We argue that this is associated with a reduction in the risk of over "overconsumption" associated with WSR ownership. Despite consuming more during periods with IBR structures, households were *less* likely to consume in higher blocks and were *more* likely to consume close to, but under, the block boundaries. It is this stark contrast between the outcomes of different pricing structures that highlights the importance of unintended consequences of the interaction of different policy instruments.

A household's ability to select into the program raises concerns about endogeneity. We address this issue by instrumenting for WSR ownership using the fact that a random subset of households received additional notice of the availability of the WSR.

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[7] Increasing block rate pricing sets a constant marginal price within a block, but includes an upward jump in price when consumption increases from one block to the next. Where "block" refers to a range of consumption levels over which the marginal price charged per unit is the same.

[8] In the electricity sector see for example Matsukawa (2004) and Sexton *et al.* (1986)

The next section, presents background information on the context for our model. Section Three outlines a model of consumer behavior with and without uncertainty. It considers two distinct pricing schemes: one where consumers face a constant marginal price and one where consumers face a per unit penalty for consuming beyond a particular threshold. Section Four describes the Aurora WSR reader program and the data for our empirical analysis. Section Five reports the empirical tests of the effect of uncertainty combined with pricing structure in the context of residential water demand. The last section concludes with a discussion of the policy implications of our analysis.

II. Background

Why might consumers be uncertain about the quantity they consume? For goods such as water, electricity and cell phone use, two reasons stand out. First, it may be difficult to monitor consumption of these goods in particular applications. In order to find out how much electricity or water a particular appliance uses, one needs to turn off all appliances, locate the meter, take a reading before the appliance is used, let the appliance run its cycle, then take a reading, again, from the meter. The cost to acquire such information may be prohibitively high given the relative budget share involved. Second, and potentially more important, is the nature to which consumers are billed for these goods. For these goods, consumption is made prior the resolution of uncertainty. That is, for the consumption of water, electricity and cell phone usage, the actual quantity consumed becomes known only after it is "too late" for the consumer to change her mind. These goods are used in small quantities over many different uses and are billed after consumption takes place. It is these two facets of consumption that make these goods particularly interesting.

Quantity uncertainty likely manifests itself in two ways. First, because households are unable to monitor their consumption, they may consume more or less than they had hoped over the course of the bill period. Second households may develop biased beliefs about their actual water use due to the relative costliness of monitoring actual consumption across bill periods. As a result, two different types of consumers are likely to emerge. The first correspond to those who know how much they consume on average, but might consume more or less than they actually intend. The second correspond to those consumer's who because they are unable to monitor their actual consumption, have also developed biased beliefs about the amount they typically consume. These consumers may not read their bill at the end of the month or may receive inaccurate information about their consumption habits. Similar to above, *actual* consumption is likely to differ from *perceived* consumption at any given moment; however, for these consumers, actual consumption over a given period will also tend to differ from perceived consumption. In both instances, the amount consumers think they consume is likely to differ from how much they are billed for at the end of the month. Our goal is to shed light on how each of these two consumer types would behave differently if uncertainty was eliminated. Previous research, with similar types of treatments, has not considered this issue formally and/or have not consider both of these roles, focusing on them isolation. Sexton *et al.* (1986) report on the interaction of information and time of day pricing in electricity consumption. This highlights the impact of shifting consumption within the billing cycle. Not surprisingly, that when given a monitoring device, households move consumption to off peak periods and aggregate consumption rose by an average of 5.5%. This is due to the interaction of the time of day pricing with the monitor. As prices fall, as in the case

of time of day pricing, we would expect consumption to shift and if households can better monitor their consumption, it should rise more. From a utility manger's perspective, this movement of consumption may be beneficial to smooth consumption of the day and reduce peak load periods even though aggregate consumption rises.

Matsukawa (2004) considers the role of an electricity monitoring device in the presence of a constant price structure on electricity consumption and finds that, in general, households conserve in the presence of better information. Given the pricing structure, this study highlights the use of information to show where in the house electricity is consumed. These two studies, taken together, highlight the importance of the pricing structure in influencing the role that new information plays for individual choice. Information campaigns, such as these monitoring devices, together with different pricing structures imply that households may face a different marginal price depending on how much they consume. For quantity uncertain households who are subject to non-linear pricing, the financial penalty for over consuming is potentially not equal to the penalty for under consuming, as is the case under constant marginal pricing schemes.

The use of increasing block rate (IBR) pricing schemes provide one such example. IBR pricing sets a constant marginal price within a block, but includes an upward jump in price when consumption increases from one block to the next.[9] The term "block" refers to a range of consumption levels over which the marginal price charged per unit is the same. IBR have become increasingly popular among water and electricity utilities. In 1997, about one-third of U.S. residents were sold water priced according to an increasing block rate structure, up from around 4% in 1982 (Olmstead, *forthcoming*). IBR

[9] Note the similarities between the IBR pricing schemes used by many utilities and the way in which cellular phone minutes are often priced. Many cellular phone plans offer a fixed number of minutes at zero price, for consumption beyond this point consumers face a large per minute charge.

pricing is intended to promote conservation. This format penalizes large water users with increases in the per unit price for consumption beyond certain thresholds.

We may view this choice of consumption as an uncertain commitment to consumption in a manner similar to Chetty (2006) and Chetty Szeidl (2007). Consumers make an unknown commitment to consumption prior to the realization of uncertainty. In Chetty (2006) and Chetty Szeidl (2007), that commitment is in housing with an unknown labor supply shock. They find that pre-commitment to a consumption level may reveal estimates of risk aversion that are considerably lower than previously estimated. Similarly, our findings show that consumers may act as if they are risk averse when in fact they are risk neutral. This perceived "risk aversion" is a function of the pricing structure together with uncertainty and not a function of preferences

III. Decision Making under Quantity Uncertainty

We develop two models, one with consumers who are certain about consumption and another where consumers are uncertain about consumption quantities. Each model is developed with constant price and with increasing block rate pricing structure. We use an increasing block rate structure for two reasons. (1) It is a rate structure that penalizes consumers for consumption beyond a certain threshold and is commonly used in water pricing. (2) In the empirical section, the municipality under consideration uses an increasing block rate structure.

Basic Theoretical Models

Assume consumers have preferences defined over two goods: a good,w, whose realized consumption level is potentially uncertain and a numeraire good, x. The consumer's problem is to maximize utility subject to a budget constraint, denoted M.

We assume that the consumer fully exhausts her income so that we may rewrite numeraire consumption as: $x = M - c(w)$. Where the price of the numeraire is normalized to unity and $c(w)$ is the total expenditures on *w*. To focus the analysis on the role of risk aversion in this one good, utility is assumed additively separable between *w* and *x*.[10] We can then write the consumers problem as:

$$\max_{w} u(w) + v(M - c(w)) \tag{2.1}$$

where both *u* and *v* are assumed to be twice differentiable and increasing in their respective arguments. Additionally, assume that *u* and *v* are concave. The first order conditions for this problem depend on the pricing structure of *w* and we will go through each of these in turn.

As an extension to this basic quantity certainty model, we develop a parallel model where the quantity of *w* is uncertain at the time the decision to consume takes place, i.e. consumers choose a "perceived" or "target" consumption level which may differ from the actual level of consumption. Let this targeted level of consumption be denoted by w^p. Further denote their actual consumption after uncertainty has been revealed as w^a, which is unknown until the consumer receives her bill.[11] Of importance, in this setting, is that consumers only learn about actual consumption *after* they have already consumed the good.

As before, we assume that residual income after paying the bill is spent on the numeraire so that $x = M - c(w^a)$. Note that consumers are billed on their actual use, w^a,

[10] If we relax this assumption of additive separability, the results would be affected by the degree to which consumption of these two goods interact. Obviously, if there is a complementary relationship between *w* and *x* our results would be exacerbated and if *w* and *x* are substitutes the results would be muted.

[11] In one sense, we may think of w^p and w^a as a collection of decisions the individual makes over the course of a billing cycle.

an amount that is potentially different from what they think they have consumed over the course of the billing cycle. Thus, uncertainty occurs as a result of not knowing how much money is going to be "left over" to be spent on the numeraire consumption. Unintentionally consuming more (less) than the target amount results in having less (more) residual income to be spent on the numeraire good.

From a household's perspective actual consumption, w^a, can be thought of as a random variable, conditional on the consumer's choice of an anticipated level of consumption, w^p.[12] Denote the probability density function corresponding to the distribution of w^a as $f(w^a \mid w^p, b)$, where w^p and b are two of the parameters of the distribution such that $E[w^a] = w^p + b$. Here, we denote b as the bias of the individuals perceptions about consumption. Further, suppose that w^a is symmetric with mean $w^p + b$.

For a quantity uncertain consumer, their objective is to maximize *expected* utility subject to the budget constraint through choices of w^p and x. Embedding the budget constraint, we can write the problem as:

$$\max_{w^p} u(w^p) + \int_{-\infty}^{\infty} v(M - c(w^a)) f(w^a \mid w^p, b) dw^a \tag{2.2}$$

Note that the consumer's choice of w^p impacts not only the utility she derives from consumption but also through the distribution governing how much residual income is left for numeraire consumption.[13]

[12] The anticipated quantity could differ from the actual quantity because households to not know the rate at which appliances use water or the rate at which households utilize these appliances. It may be difficult to monitor either of these two types of uncertainty even if an individual constitutes the household.

[13] It is worth noting that the set up of the quantity uncertain model is similar to the set up for a precautionary savings model as in Leland (1969) or Ritchken and Kuo (1988). In their framework, the decision involves choices in a two period model with distinct utility functions in each period

Constant Marginal Pricing System

With this basic structure, consider first the case where w is priced according to a constant marginal price. Suppose that $c(w) = \underline{p}w$. In the quantity certain case, we can rewrite the general problem as:

$$\max_{w} u(w) + v(M - \underline{p}w) \tag{2.3}$$

Let w^* denote the solution to this problem, then w^* is defined by:

$$u_w(w^*) = \underline{p}v_x(M - \underline{p}w^*) \tag{2.4}$$

where subscripts denote derivatives. Note that $v_x(.)$ can be thought of and we will refer to it as, the marginal utility of income.

For the quantity uncertain case, the problem with a constant marginal price system can be rewritten as:

$$\max_{w^p} u(w^p) + \int_{-\infty}^{\infty} v(M - \underline{p}w^a) f(w^a \mid w^p, b) dw^a \tag{2.5}$$

Let w^{p*} denote the solution to this problem, then w^{p*} is defined by:

$$u_w(w^{p*}) = \underline{p}\int_{-\infty}^{\infty} v_x(M - \underline{p}w^a) f(w^a \mid w^{p*}, b) dw^a \tag{2.6}$$

This occurs precisely from the symmetry assumption of w^a.[14] Equation (2.6) simply states that w^{p*} occurs where the marginal utility of w is equal to the expected marginal utility of income.

(corresponding to our separability assumption), with no discounting, and an uncertain income which is dependent upon decisions made in the first period. Hence, if an individual chooses to consume less than they would have in a certain world, we may think of that as simply precautionary savings for numeraire consumption.

[14] Note that under the assumption that w^a is normally distributed with mean $w^p + b$:

$$f_{w^p}\left(w^a; w^{p*}\right) = -f_{w^a}\left(w^a; w^{p*}, b\right)$$

As a result, the first order condition can be rewritten as

$$u_{w^p}\left(w^{p*}\right) = \int_{-\infty}^{\infty} v\left(M - \underline{p}w^a\right) df\left(w^a; w^{p*}, b\right)$$

Integrating by parts we have:

Equations (2.4) and (2.6) provide the starting point from which comparisons between quantity certainty and uncertainty under a constant marginal price system can be made. Not surprisingly, the impact of uncertainty on demand is dependent on the curvature of $v(.)$. As a first step, suppose that consumers are risk neutral with respect to numeraire consumption.

Proposition 1: If consumers are risk neutral with respect to numeraire consumption then $w^{p*} = w*$, independent of the consumers bias on beliefs about consumption.

Proof:

See Appendix.

Hence, if individuals are risk neutral they will always target the same quantity independent of the role of uncertainty. But beliefs play into the realization (i.e. their "actual" consumption levels). If individuals underestimate (overestimate) their water consumption, *b > 0 (b < 0)*, then they will on average consume more (less) than they targeted which will affect resulting utility. If the resulting difference between expected and resulting utility is large, then we might expect individuals to re-evaluate their expectations about actual water use (i.e. attempt to eliminate the bias). However, if this difference is small, the costs associated with refining one's expectations may exceed the potential benefits. In which case, a permanent bias may exist.

$$u_{w^p}\left(w^{p*}\right) = \left[v\left(M - \underline{p}*\infty\right)*f\left(\infty; w^{p*}, b\right) - v\left(M + \underline{p}*\infty\right)*f\left(-\infty; w^{p*}, b\right)\right] - \int_{-\infty}^{\infty} -\underline{p}v_x\left(M - \underline{p}w^a\right)f\left(w^a; w^{p*}, b\right)dw^a$$

Or

$$u_{w^p}\left(w^{p*}\right) = \underline{p}\int_{-\infty}^{\infty} v_x\left(x\right)f\left(w^a; w^{p*}, b\right)dw^a$$

Consider now, the case when consumers are risk averse in numeraire consumption. To recover specific insights additional assumptions about the structure of the numeraire sub-utility function are needed. We assume that the third derivative of v is positive. This assumption is equivalent to assuming that individual's risk aversion is decreasing with respect to wealth. Those who exhibit this property are willing to take more risk as they become wealthier.[15]

Proposition 2 considers the case of risk averse consumers who also have unbiased beliefs about w.

Proposition 2: If consumers are risk averse with respect to numeraire consumption, $v_{xxx}(.) \geq 0$, and have unbiased beliefs about consumption, $b = 0$, then $w^* \geq w^{p*}$. If $v_{xxx}(.) > 0$ then this becomes a strict inequality.

Proof:

See Appendix.

From Proposition 2, individuals that have unbiased beliefs about consumption will target quantities less than what they would have under a constant marginal price system had not been quantity uncertain. Interesting to note is that while risk neutral households with biased beliefs may display behavior consistent with risk aversion ($b > 0$) or risk loving ($b < 0$), these responses are not tied to the curvature of the numeraire sub-utility function.

We now allow for the potential of biased beliefs to interact with risk aversion. We are interested not only in how biased beliefs affect targeting consumption but also

[15] This assumption is consistent with much of the literature on precautionary savings.

actual consumption. Let $w_{b>0}^{p*}$, $w_{b=0}^{p*}$, and $w_{b<0}^{p*}$ denote optimal target consumption levels for an individual if they overestimate, have unbiased expectations (corresponds to Proposition 2), and underestimate their actual use. Biased beliefs affect the mean of the distribution of actual consumption. The distribution has the same shape just shifted by *b*. Hence, when risk adverse consumers have biased beliefs the bias changes not only the actual consumption but the targeted consumption.

Corollary 1: $w_{b>0}^{p*} \geq w_{b=0}^{p*}$ *for risk averse consumers who underestimate* ($b > 0$) *their actual use.* $w_{b<0}^{p*} \leq w_{b=0}^{p*}$ *for risk averse consumers who overestimate* ($b < 0$) *their actual use.*

Proof:

See Appendix.

Corollary 1simply states that individuals who underestimate (overestimate) their consumption will *target* quantities that are greater (less) than what they would target absent the bias.

What impact does this have on average *actual* consumption? Note that Proposition 2 and Corollary 1 reflect two different aspects of quantity uncertainty. With or without the bias, the risk associated with an uncertain outcome causes risk averse individuals to consume less. Biased expectations cause them to over or underestimate the expected marginal value of income and the risk associated with any particular level of target consumption. The resulting effect on average actual consumption depends on the sign of the bias. For individuals who overestimate, expected actual consumption will be less than what they would consume absent the uncertainty ($E\left[w^a\right] \leq w_{b<0}^{p*} < w_{b=0}^{p*}$). For

those who overestimate their use, the effect is unclear. It depends on the magnitude of the bias and how risk averse the consumer is. Table 1 provides a summary of these results.

Table 1: Summary of Constant Marginal Price Results

Constant Marginal Rate	b=0	b>0	b<0
Risk Neutral	$E\left[w^{a*}\right] = w^{p*} = w^*$	$E\left[w^{a*}\right] = w^{p*} + b > w^{p*} = w^*$	$E\left[w^{a*}\right] = w^{p*} + b < w^{p*} = w^*$
Risk Averse	$E\left[w^{a*}\right] = w^{p*} \leq w^*$	$w_{b>0}^{p*} \,?\, w^*$ $E\left[w^{a*}\right] ?\, w^*$	$E\left[w^{a*}\right] = w_{b<0}^{p*} + b < w^{p*} = w^*$

Increasing Block Rate Structure

Now, consider the case of a two-tiered pricing structure of the form:

$$c(w) = \begin{cases} \underline{p}w & if\ w \leq \ddot{w} \\ \overline{p}(w - \ddot{w}) + \underline{p}\ddot{w} & if\ w > \ddot{w} \end{cases} \tag{2.7}$$

Where $\underline{p}$ corresponds to the price of the w in the first block of consumption, $\overline{p}$ the price in the second block, and $\ddot{w}$ is the amount available for first block consumption.[16]

Under this pricing structure, the consumer operating under certain quantities will solve:

$$\max_w u(w) + \begin{cases} v\left(M - \underline{p}w\right) & if\ w \leq \ddot{w} \\ v\left(M - \overline{p}w + (\overline{p} - \underline{p})\ddot{w}\right) & if\ w > \ddot{w} \end{cases} \tag{2.8}$$

Residual income is rewritten to reflect the two processes that are taking place when a consumer chooses to consume in the second block. First, they react to the marginal price in the second block. Additionally, since not all of w is priced according to the second block price, income is augmented to reflect the fact that it requires a smaller total

[16] Note that, without significant loss of generality, we have set the price of the first block equal to the price charged under the constant marginal pricing structure in order to better compare the results between the two pricing structures.

expenditure. This is due to the lower price for w consumed in the first block. Let $\mathfrak{w}^*$ be a solution to (2.8), which is characterized by:

$$u_w(\mathfrak{w}^*) = \begin{cases} \underline{p}v_x\left(M - \underline{p}\mathfrak{w}^*\right) & if\ \mathfrak{w}^* \le \mathfrak{b} \\ \overline{p}v_x\left(M - \overline{p}\mathfrak{w}^* + (\overline{p} - \underline{p})\mathfrak{b}\right) & if\ \mathfrak{w}^* > \mathfrak{b} \end{cases} \tag{2.9}$$

Before continuing, two items are worth noting with regard to the quantity certain case with increasing block rate pricing. First, when $\mathfrak{w}^* \le \mathfrak{b}$, $\mathfrak{w}^* = w^*$. That is, individuals would consume less than the threshold amount in the absence of the block rate structure will consume the same regardless of whether or not they face a constant or block rate pricing structure.[17] This is not true for the quantity uncertain case. Moreover, increasing $\overline{p}$ will have no effect on w^* for those individuals within the first block.[18] The result does not hold true when $\mathfrak{w}^* > \mathfrak{b}$. In this case $\mathfrak{w}^* < w^*$ due to the block rate pricing structure; this provides an incentive to reduce consumption when quantity demanded is above the threshold amount. [19]

The problem is a bit more complicated for cases with uncertain quantities under an IBR. The consumer's problem becomes:

$$\max_{w^p}\ u\left(w^p\right) + \int_{-\infty}^{\mathfrak{b}} v\left(M - \underline{p}w^a\right) f\left(w^a \mid w^p, b\right) dw^a + \int_{\mathfrak{b}}^{\infty} v\left(M - \overline{p}w^a + \left(\overline{p} - \underline{p}\right)\mathfrak{b}\right) f\left(w^a \mid w^p, b\right) dw^a \tag{2.10}$$

[17] It is important to remember that we are operating in the short term, under the assumption that capital is fixed.

[18] The same is not true regarding a change in $\underline{p}$ for those with $w^* > \mathfrak{b}$.

[19] Together, these two attributes are behind the growing popularity of increasing block rate pricing structures. Increasing the per unit price for consumption beyond $\mathfrak{b}$ allows policy makers to target "high consumption" households without effecting the demand of those households who consume less than the threshold, where high consumption would be determined by the water service provider. In effect, the block rate structure attempts to reflect both equity and efficiency criterion.

Let $\tilde{w}^{p*}$ be a solution to equation (2.10), then $\tilde{w}^{p*}$ is defined by:

$$u_w\left(\tilde{w}^{p*}\right) = \underline{p}\int_{-\infty}^{\hat{w}} v_x\left(M - \underline{p}w^a\right) f\left(w^a; \tilde{w}^{p*}, b\right) dw^a + \overline{p}\int_{\hat{w}}^{\infty} v_x\left(M - \overline{p}w^a + (\overline{p} - \underline{p})\hat{w}\right) f\left(w^a; \tilde{w}^{p*}, b\right) dw^a \quad (2.11)$$

As before, (2.9) and (2.11) serve as departure points for identifying the effects of quantity uncertainty on demand. We begin by comparing $\tilde{w}^{p*}$ and $\tilde{w}^*$ under the assumption that individuals are risk neutral with respect to numeraire consumption. In this situation, the effects of uncertainty will depend on the level of the consumer's target consumption as compared to the block boundary under certainty. Proposition 3 formalizes the result for individuals who consume only in the first block whereas Proposition 4 considers individuals who consume in the second block in the quantity certain case.

Proposition 3: If individuals are risk neutral in numeraire consumption, have unbiased beliefs about consumption, face a two-tiered price structure for w, and $\tilde{w}^* \leq \hat{w}$ then $\tilde{w}^{p*} < \tilde{w}^*$.

Proof:

See Appendix.

Proposition 4 provides the analog of Proposition 3 for individuals that are consuming above the first block boundary in the certain consumption case.

Proposition 4: If individuals are risk neutral in numeraire consumption, have unbiased beliefs about consumption, face a two-tiered price structure for w, and $\tilde{w}^* > \hat{w}$ then $\tilde{w}^{p*} > \tilde{w}^*$.

Proof:

See Appendix.

Propositions 3 and 4 are important because they suggest that risk neutral consumers, consuming below the block threshold, will behave *as if* they are risk averse when facing an IBR even if they have unbiased expectations. Alternatively, risk neutral consumers, consuming above the block threshold will behave as if they are risk seekers.

Consider the situation of risk averse preferences together with the assumption about third derivative of the sub-utility function. In order to gain some intuition about the results, let us first rewrite the consumer's problem. Let $a = \overline{p} - \underline{p}$; a corresponds to the difference in price between blocks one and two. As a first case, consider those individuals that, in a certain world, would consume below the block boundary. Then the consumer's problem for an IBR under uncertainty can be written as:

$$\max_{w^p} u(w^p) + \int_{-\infty}^{\mathbb{H}} v\left(M - \underline{p}w^a\right) f\left(w^a \mid \mathbb{W}^{p*}\right) dw^a + \int_{\mathbb{H}}^{\infty} v\left(M - \underline{p}w^a + a\left(\mathbb{H} - w^a\right)\right) f\left(w^a \mid \mathbb{W}^{p*}\right) dw^a \tag{2.12}$$

Taking the first order condition, we have:

$$\begin{aligned} u_{w^p}\left(\mathbb{W}^{p*}\right) = {} & \underline{p}\int_{-\infty}^{\mathbb{H}} v_x\left(M - \underline{p}w^a\right) f\left(w^a; \mathbb{W}^{p*}\right) dw^a + \\ & \underline{p}\int_{\mathbb{H}}^{\infty} v_x\left(M - \underline{p}w^a + a\left(\mathbb{H} - w^a\right)\right) f\left(w^a; \mathbb{W}^{p*}\right) dw^a + \\ & a\int_{\mathbb{H}}^{\infty} v_x\left(M - \underline{p}w^a + a\left(\mathbb{H} - w^a\right)\right) f\left(w^a; \mathbb{W}^{p*}\right) dw^a \end{aligned} \tag{2.13}$$

The effects of uncertainty can be decomposed into three categories. The first "risk" is associated with the concavity of the numeraire sub-utility function and is the risk aversion associated with preferences. Through Jensen's inequality, the concavity pushes households that, in a certain world, would consume in the first block to consume less than they would have in a certain world. We see this exactly from Proposition 2 for the

constant price and is still reflected here. The second is the income effect brought about by the increasing block rate structure. If a consumer receives a draw on consumption such that they consume in the second block but meant to consume in the first block. They receive a "discount" on *w* because lower blocks are priced lower than where they are consuming. They are not penalized on over consuming for all the consumption, only that which is over the thresholds consumption level. This is reflected in the second term. Finally, there is the price effect of consuming *w* at a high price in the second block. This is reflected in the third term of equation (2.13). Proposition 5 summarizes the results for households that are targeting consumption below the block boundary.

Proposition 5: If individuals are risk averse and have a positive third derivative in numeraire consumption, have unbiased beliefs about consumption, face a two-tiered price structure for *w*, and $\mathcal{W}^* \leq \mathcal{H}$ then $\mathcal{W}^{\rho^*} \leq \mathcal{W}^*$. Additionally, they consume less than the risk neutral consumers.

Proof:

See Appendix.

What about individuals consuming above the block boundary in the certain case with risk averse preferences? When consumers are risk neutral (Proposition 4) only the risk of price comes into play. This is what allows us to be clear about the sign of the effect on individuals above the block boundary. When both types of risk are present, we can not be certain what the combined effect of will be. For those above the block boundary, uncertainty opens up the possibility that they may face a lower marginal price than they expected. The question becomes whether the level of risk aversion outweighs the effects

of drawing a low consumption (below the block boundary) or the reverse. Risk aversion pushes consumption down whereas the price structure pushes consumption up when certain consumption falls above the block boundary. Which effect dominates depends on the magnitude of the differences in price and the degree of risk aversion. This becomes an empirical question that will be taken up in the next section.

The theoretical model suggests a number of testable hypotheses. First, there is a difference in how households react to information under constant and increasing block rate structures. The theoretical model suggests that information will have a potentially different effect on households who face an increasing block rate structure (for households under the block has greater incentives for households over the block has less incentives). From Proposition 5 we know that households that, under certainty, consume below the block boundary will consume less than both the certain consumption and the uncertain constant price consumption. For households with unbiased beliefs above the block boundary, the effect of uncertainty under block rate pricing is unclear.

IV. Aurora and the Water Smart Reader Program

Background

A unique data set allows the issues raised in our theoretical analysis to be considered directly. The data are taken from the customer records for the City of Aurora, Colorado Water Utilities. We analyze the water consumption habits of over 88,000 residential water households located in Aurora, Colorado over the period 2000 to 2005. [20] Beginning in 2002, rapid population growth combined with the onset of one of the most severe droughts on record, led water officials to introduce a significant number of

[20] This is a subset of the total records for the City of Aurora. We only consider households who do not move within Aurora in the sample period. This provides us with an unbalanced panel dataset of households with a fixed location as some households move into and out of the data set over time.

policies intended to reduce both the short and long run demand for water. Of these, two particular sets of policies are relevant for the study at hand: a series of rate structure changes beginning in 2002 and the introduction of the Water Smart Reader rebate program in 2005.

Prior to July 1, 2002, residential water was priced at a constant marginal price throughout the entire year; all households faced the same per unit charge for water regardless of the quantity they consumed. In July of 2002, the City began using a three-tiered block rate structure primarily during the summer months[21]. The three-tiered structure was designed to give relatively low cost water to satisfy the "typical" indoor needs of a "typical" household; an increased price on water to meet "typical" outdoor needs, and finally a severe price increase for water consumption in excess of the "typical" needs of a household. It is important to note that at various points during the 2002-2005 period, both the parameters of the price structures (i.e. block width and price) and the type of structure consumers faced changed. Thus, over the sample period we observe both variation in prices across rate structure types (i.e. marginal versus IBR), as well as variation in prices within each of the rate structures.

This change in price structure is significant for several reasons; most notably the switch from a relatively simple uniform price structure to a complex set of increasing block rate structures under which consumers incur per unit penalties for consuming beyond particular thresholds. Previous research suggests that while consumers may be aware of the fact that excessive water use leads to significant charges, they may be

[21] It is worth noting that IBR pricing was primarily, but not exclusively used during the irrigation season over the period of study.

unaware of the exact details of the rate structure itself.[22] That is, they may based decisions on average price paid last month (or some other price) yet still be aware that they face a penalty if they consume beyond a certain threshold. Whether or not they know the exact amount of the penalty is irrelevant for the purposes of this paper.

In the spring of 2005 households were offered the opportunity to purchase, at a reduced cost, an electronic device that would allow them to more easily see how much water they are using at any moment in time as well as their cumulative water use for a billing cycle. These devices are referred to as Water Smart Readers (WSR). Households that own a WSR have access to real time information about their water use. By comparison, households who do not own a WSR must wait until after the end of each billing period to receive this information. Note that owning a WSR does more than increase the reporting frequency. Households using a WSR may adjust behavior during the billing period in response to learning that their target amount has differed from their actual amount up to that point in the bill period. By comparison, households without a WSR can't make this type of adjustment prior to receiving their bill because they do not observe the difference in actual versus perceived use until they receive their bill.

Data and Estimation

Our data set includes monthly observations of household consumption, price structure, length of the billing period, WSR ownership, who received an advertisement for the WSR, and when watering restrictions were in place. In addition we collected temp and precipitation data from the National Climatic Data Center. Table 2 presents

[22] It is not clear if customers would have appreciated all the details of the price structure. For example see Chicoine and Ramamurthy (1986) or Nieswiadomy (1992)

definitions and source information for the variables used in the analysis presented in Section V. Table 3 provides summary statistics of these variables.

Table 2. Variable Definitions

Variable	Definition	Units	Source
consum	household consumption per billing period	1000 Gal	Aurora
wsr	indicator variable, equal to one if household purchased a Water Smart Reader	0-1	Aurora
blockrate	Indicator of block rate period	0-1	Aurora
restrict	indicator variable, equal to one if restrictions where in place at some point during the current bill period	0-1	Aurora
p(i)	CPI price paid per thousand gallons in the ith block	1999 $'s	Aurora
blprddays	length of current bill period	days	Aurora
avemaxt	average daily maximum temperature over the course of the current bill period	ºF	NCDC
totprecip	total precipitation over the course of the current bill period	Inches	NCDC

Table 3: Summary statistics

Variable	Mean	Min	Max	SD
consum	9.70	1	639	8.35
wsr	0.001	0	1	0.041
blockrate	0.298	0	1	0.457
restrict	0.326	0	1	0.469
p(1)	2.26	1.75	3.05	0.52
p(2)	4.14	3.33	5.28	0.71
p(3)	5.53	3.69	7.92	1.52
blprddays	30.36	27	35	2.30
avemaxt	65.27	38.03	94.48	15.72
totprecip	1.24	0	6.15	1.19

Of importance is that we observe both households who eventually purchased a WSR (WSR households) and households who did not purchase a WSR (non-WSR

households) before and after they receive the device, during periods with increasing block rate pricing and with a constant price. During the period of study 1014 WSR were purchased through the subsidized program.

Overview of Effects of WSR Ownership

Before presenting our formal statistical analysis, we motivate our discussion of the effects of uncertainty on demand with a series of illustrations, focusing specifically on residential water demand patterns over the years 2004-2005. We focus on these years for our graphical analysis because over this period prices and price structures remained constant and climatic conditions were comparable. The only aspect, from a policy perspective, that would have potentially changed consumption is the purchase of a WSR.

The hypotheses developed in Section III all predict quantity uncertain behavior to differ from quantity certain behavior. However, contrary to intent of the program, we observed an increase in water use among WSR households. As presented above, two possible explanations are consistent with such an increase. First, the WSR may be correcting biased expectations about water use. That is, prior to owning a WSR, households might have *underestimated* their water use. Second, households may have consumed less than their ideal amount, because of the fear of getting penalized by the rate structure for consuming beyond the block boundary. Since water consumption makes up such a small proportion of the households budget, the level of risk aversion will be small.

If the former is the dominant factor, we would expect the effect to be to reduce water consumption regardless of the type of rate structure and we wouldn't necessarily expect to observe any "strategic" differences in consumer behavior within a block

structure. That is, we wouldn't expect the location of households relative to the block boundaries to differ beyond the obvious that the consumption of households who overestimated their use would be shifted to the right.

Figures Figure 1, consider now, where in the price schedule households are consuming in the presence of a WSR and without. These consumers are reducing the probability of consuming in a higher block. By combining the quantity consumed with the probability, households are better able to target a desired quantity of consumption and not simply be at the mercy of the randomness of water consumption. Hence it is not that households have biased beliefs about water consumption but that they want to target a level, an optimal level, and the use of a WSR allows them to do so with a decreased probability of consuming in higher priced blocks. In the next few sections, we formalize these observations.

Figure 1: Marginal Block Consumption, Before and After WSR

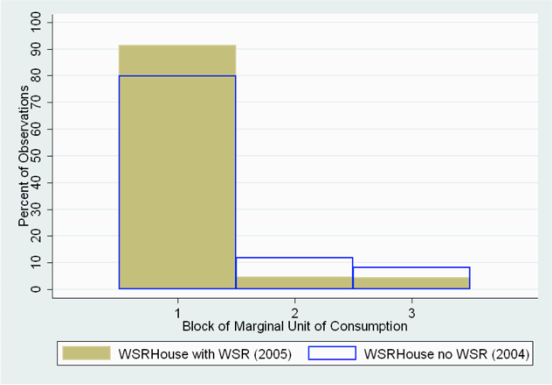
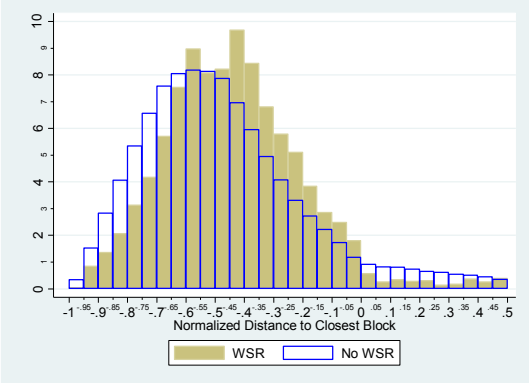


Figure 2 displays the distribution of distance to block boundaries for water smart reader households and non-water smart reader households. Values greater than zero indicate that the household was above the closest block. Values less than zero indicate that the household was below the closest block (note households consuming in the first block are considered consuming below the closest block). This figure shows this

combination of decreased probability and increased consumption. Households with water smart readers are able to reduce positive random draws and optimally consume below a block boundary. Households with water smart readers that are below the block boundary are able to better target an optimal quantity without the fear of consuming over the block boundary. In aggregate, there are more households that fit the latter description and hence aggregate consumption increases.

Figure 2: Distribution of Normalized Distance to Closest Block, with and without WSR (2004-2005)



As Propositions 3 and 4 imply the effect of WSR ownership appears to differ based on the proximity of the house to the nearest block. Households below the nearest block boundary, increase their consumption, consuming closer to the closest block. Households that we previously consuming above a block boundary may either move below the block boundary through either the elimination of bias or through betting targeting behavior. For households still consuming above a block boundary, there is the push and pull of various factors as discussed in the latter part of the theoretical section.

V. Empirical Results

Since the data contains two price structures, a constant and an increasing block rate, we can bound the role of the joint impact of bias and risk aversion if the impact of the water smart reader is negative during the constant price structure period. During a constant price period, there are two motivating factors for household consumption under uncertainty, the curvature of the utility function and the bias in beliefs. The curvature acts to push consumption down since errors of over consumption is slightly more costly than under consumption under uncertainty. Hence, by eliminating uncertainty, households should increase consumption. Much of the literature suggests that the bias on households perceptions of consumption is underestimated. Hence, by removing the bias, households should decrease consumption. If on net these effects are negative (positive), we may bound the bias (risk aversion).

Second, where households consume in the block rate structure has an effect on the role of uncertainty. We know that households that consume below the block boundary will react to both the marginal price as well as the price of the higher blocks through risk aversion of consuming in higher blocks. The ability to know where you are will lessen the impact of higher blocks through the elimination of the increased "risk aversion" brought about by the rate structure. Household will be better able to achieve consumption level that falls within the optimal facet of the price structure.

To begin the testing of these hypotheses we estimate a simple residential water demand model using expanded difference-in-difference framework which accounts for unobserved household heterogeneity by including household fixed effects. The general form of the estimation is:

$$\ln(consum_{it}) = \alpha + \beta_1(WSR_{it}) + \beta_2(Blockrate_t) + \beta_3(WSR_{it} * Blockrate_t)$$
$$+\beta_4(\ln(P_{1_t})) + \beta_5(\ln(P_{2_t})) + \beta_6(\ln(p_{3_t})) + \beta_7(numbillingdays_{it})$$
$$+\beta_8(ave\max temp_t) + \beta_9(totalprecip_t) + \beta_{10,month}(monthly\,dummies) + \varepsilon_{it}$$

In these first two specifications only the error structure changes. In the fixed effects model we replace the error term with $\mu_i + \varepsilon_{it}$, where μ_i is a household fixed effect.

Absent uncertainty, under an IBR structure, households react to more than just the marginal price, as the price of the blocks *below* the marginal block are also relevant via an income effect (see Olmstead (2009) for a more lengthy discussion of this). However, under uncertainty the set of prices relevant to the consumer's problem also includes the price of blocks *above* the marginal block of consumption. That is, despite the fact that most households consume in the first block (Figure 1), the price of the second and third blocks is likely to affect their behavior when they are uncertain. However, the nature of this relationship is unimportant since the present study is not concerned with estimating the impact of price but of type of price structure and information. We abstract from using either marginal price or average price in our estimation. Whereas the vast majority of the literature aimed at estimating demand for goods priced according to an IBR has focused on whether or not marginal or average price is appropriate the measure of price, we include the entire price schedule rather than any single price.[23] This is done for two reasons. First, both marginal and average price are likely to be endogenous given the IBR structure. Second, again, our goal is only to control for price, not estimate its effect on quantity demanded. Finally, we are able to see which of the prices has the greatest

[23] We have also estimated the model using a lagged average price as well as instrumenting for the price and the results for the other coefficients are similar in magnitude.

impact on the decision of the household in where to locate within the entire block structure.

The reality is that we do not know how much households know about price, which prices they respond to, or what type of weighting system they place on prices in different blocks; all information that would be necessary to argue in favor of dicrete-continuous choice model[24], average price, or marginal price models. Since we are not concerned with formally estimating the how consumers respond to price, we only need to assume that the actual prices are correlated with the prices incorporated into each households decision process. Differences in how households incorporate the rate structure parameters into their decision process are accounted by including household fixed effects.

This first set of estimates includes a number of time varying controls including, month and year dummy variables, temperature and precipitation controls, the number of days in the billing cycle, dummy variable to indicate a whether or not block pricing was in effect, a dummy variable for the presence of a WSR, an interaction term between the WSR and the block rate pricing period, and, finally, an indicator for whether or not the household eventually purchased a water smart reader. These last four terms allow us to see whether or not water smart reader households behave differently prior to purchase than other non-WSR households, the role of the WSR in constant and block rate periods and the effect of the block rate structure as a whole. The coefficient on WSR will represent the net effect of the elimination of the bias and the increase in consumption

[24] See Hewitt and Hanemann (1995) for a discussion of the use of the discrete-continuous choice model as applied to water demand estimation under block rate structures. In a follow-up paper (Strong and Goemans (2010)) we have estimated the discrete-continuous choice model in order to understand how price responsiveness changes with information. But, this does not allow us to tease out the effects of the block rate structure and WSR independently as well as jointly.

from the elimination of the "fear" of over consumption during constant pricing. The sum of the WSR coefficient and the interaction of the WSR and the block rate will give us the added information of the effect of the WSR during block rate periods. Finally, the sum of the WSR, block rate and the interaction of WSR and block rate will give us a net effect of the WSR during block rate periods. The original motivation for instituting an increasing block rate structure and for distributing the WSR was to reduce water consumption. Theory suggests that the block rate structure will be more effective in reducing water consumption if there exists information uncertainty (see Proposition 5 for a discussion of this). The results for this estimation appear in the first column of Table 4.

There are a number of observations that appear in this estimation. First, the WSR coefficient is negative. There are two possible explanations for this result: (1) households underestimated their use prior to receiving the device (2) the device eliminated the risk affect associated with over/under consuming. We argue that, given the small (perceived or otherwise) income effect associated with over or under consuming, this result corresponds to elimination of bias associated with household beliefs about their water use. This implies that the role of information in the constant rate structure is on eliminating the bias of underestimating water consumption more than on the role of eliminating risk aversion. Hence, in the constant price structure the policy has the intended effect.

By comparison the interaction term between WSR and block rate structure is positive. If we sum these two coefficients, we see a positive coefficient. Contrary to the findings in the constant price structure, the risk of consuming in the next highest block outweighs the effect of the bias in targeted consumption. Hence, the price structure plays

a vital role in how consumers respond to information, as the theory suggests. Next, the block rate structure on its own has the desired effect of reducing water consumption. This negative result is consistent with Olmstead *et al.* (2007) who found that the presence of a block rate structure tended to increase the elasticity. But, the combination of the WSR with the block rate structure on net has no effect with the OLS estimation. The sum of the WSR, block rate and interaction between these two is statistically insignificant in the OLS estimation.[25] By eliminating both the bias in targeted consumption and the fear imposed by the block rate structure, the optimal consumption is unaffected by these two policies interacting. These results suggest that the block rate structure only works to reduce consumption when there exists consumption uncertainty.[26]

Finally, the water smart reader household variable is significant. This is not surprising given the large number of observations that we have. Of greater importance is the magnitude of the coefficient; which suggests that there is no a large difference between WSR households and those that do not purchase the device prior to the ability to purchase the WSR device.

There exists a few confounding problems with this estimation. First, we have included no household specific characteristics other than those pertaining to the purchase of a WSR. This is a product of the data. We do not have sufficient information to allow us to identify the household beyond the census tract. Since this data has a panel structure of monthly consumption by household from 2000-2005, we exploit this by using a household fixed effect. This will control for all time invariant household heterogeneity

[25] The sum of the coefficients is 0.0150 with a standard error of 0.123.
[26] This assumes that households do not change their capital stock of water consuming goods. The block rate structure is designed to affect these decisions as well as the intensity of use of these goods. We focus here on the intensity and not the choice of water intensive goods.

not associated with the WSR purchase. By using this fixed effect we eliminate the ability to identify whether or not households eventually purchase a WSR. These results appear in the second column of Table 4. These results are all similar in magnitude as those of the OLS estimation with the exception of the sum of the WSR, block rate and WSR interacted with block rate which is now positive and significant. The sum of the coefficients is 0.0832 with a standard error of 0.00895. Hence, through the interaction of these two policies we see a roughly 8% increase in water consumption once we control for time invariant household characteristics. This is surprising in that both policies by themselves have the desired effect but we see this unanticipated effect, from the water managers perspective, when we combine policies. Hence, when water managers throw the entire book at the problem, the results may not have the desired effect. What we see though is that households are better able to target a specific level of consumption with knowledge of the price structure and where breaks in the pricing structure occur.

Endogeneity of WSR Ownership

Up to this point, we have not taken account of the potential endogeneity of the purchase of the WSR.[27] Thus it is unclear whether or not the results presented above are due to the effects of owning a WSR or from other unobserved differences that distinguish WSR households from non-WSR households. In order to attempt to control for this, we instrument for WSR and WSR*BlockRate using various dummy variables corresponding to the advertisement of the WSR. During 2005, a number of notices were sent to households. An initial mailing announcing the program was mailed to all households. Depending on the meter reading route, households we sent a second mailing at different

[27] Figure 2 suggests that there seems to be nothing different in terms of water consumption between households that choose to purchase a WSR and those that do not and the results from the OLS estimation suggest that the differences are small in terms of consumption patterns.

times. Because of this second mailing we are able to instrument for the timing but not the purchase of a water smart reader. Hence, we focus on just those households that purchase water smart meters. Second, there may be considerable confounding problems because 2002-2003 represents the height of one of the most severe drought to affect Colorado in history. Because of this drought, additional non-pricing restrictions were in place and there was considerable media attention played to the drought. During the winter of 2003-2004 there was higher than average snowfall allowing most of the reservoirs to refill following the drought. Hence, we choose to concentrate on the 2004-2005 period for households that eventually purchase water smart readers. Using our instrument of the date of the second mailing, we instrument in a first stage regression the purchase of the water smart reader. Additionally, since we are interesting in the interaction between WSR and block rates, we instrument this cross term using the cross between the date and the presence of a block rate structure. We do this first stage using a continuous as well as limit dependent variables approach. As a first stage, we estimate this using either a fixed effects estimation or a fixed effects logit. The second stage is estimated using fixed effects. These results appear in columns 1 and 2 of Table 5, respectively, with only the relevant variables presented. Finally, column 3 of Table 5 is the same estimation as column 2 of Table 5 using this reduced sample of eventual WSR households during 2004-2005. Using this additional framework to control for endogeneity as well as the potentially confounding effects of the drought, we see that our results are robust to the specification.

Finally, theory suggests that households will react to uncertainty depending on where they locate, under certain information, in the block rate structure. In order to

control for this, we segment the WSR households during 2004-2005 into two groups, those consuming in above a block boundary and those consuming below. Since we have a three block structure, if a household consumes in the first block, we label them below a block boundary. If the household is consuming in the second block above the mid point of the block we also label them as consuming below the block boundary. If households are consuming in third block or in the first half of the second block we label them above a block boundary. We estimate these two models by using a fixed effects model, Table 6 displays these results. We see that if a household is consuming above a block boundary, the three risks as well as the bias produce a negative but insignificant result. Information seems to provide no change in the behavior of these households. As we saw in the theoretical model, we could not sign this effect because of the interaction of the different types of risk and bias. Empirically, we see that all of these effects seem to net each other out. But, if we focus in on the households that are consuming below a block boundary, they increase consumption. The price of the next highest block is no longer a risk and households are better able to target the optimal consumption of water which is higher than what would have been consumed if this "fear" were present. As the theoretical model suggests, not only does information and the pricing structure matter but where in the block rate structure households in a certain world will consume.

VI. Discussion

In this paper, we have discussed the role of quantity uncertainty under two different pricing structures. To date, only the time of day structure has been the subject of any research as to the effects demand in the presence of uncertainty. We extend this line of research to consider both the theoretical and empirical considerations of a constant

price system and an increasing block rate structure. Theory suggests that if households have unbiased beliefs about consumption then increasing information will cause an increase in consumption in a constant price system. When combined with the potential for biased beliefs, the results may result in either increasing or decreasing consumption with of the push of the bias in one direction and the pull of the averting behavior in the other. Once we move to an increasing block rate structure not only do these two forces play against each other but where households are located on the rate structure plays an important role.

Most information programs are designed to reduce the bias that consumers have about expected consumption, which has generally been thought to be an underestimate of water or electricity use. From the empirical results, we see that biased beliefs do play a major role but the impact of the pricing structure has the potential to play an even larger role in the decisions made by the household. Our findings show that information in a constant price structure has the desired effects of reducing the bias in targeted consumption and, since this bias is in over consumption, consumption decreases. Once we move to a block pricing structure, information seems to mitigate some of the effects of the pricing structure. The block rate structure causes households to reduce consumption because of the higher prices paid beyond the first block but information mutes these effects since households are better able to target the optimal consumption level. Finally, where households locate has interesting implications. Households locating above a block boundary have no change in water consumption upon receiving information while households below a block boundary *increase* consumption, contrary to the aims of the information program.

These results have important implications to water managers. First, block rate structures have the desired effect when there is poor information about consumption. Once this information problem is addressed the effects of the block rate structure on accidental over consumption are mitigated. Second, information does reduce water consumption from the reduction of biased beliefs about consumption. But, this reduction in the bias is offset because the "penalty" embedded in the pricing structure no longer plays as great a role. Households can achieve their targeted consumption level without the fear of over consumption that the increasing block rate pricing structure provides.

From a household perspective, there are considerable gains to being able to target and achieve a level of consumption. In the block rate structure, "fear" of over consumption drives households to sub-optimal allocations since over consumption is penalized greater than under consumption. From a utility perspective, the ability to target a consumption level may cause an increase in water consumption but this ability to target means that water consumption levels may be more stable, and predictable, over time. Hence, price and non-pricing policies design to encourage conservation may be more effective since households will be better able to monitor consumption.

The quick fix that many water service providers were hoping for does not seem to be apparent. As with any policy instrument, information is just one of the policy instruments that a consumer is facing. It is the combination of policy instruments that makes the ultimate effect. Hence, as better information is provided to the consumer, they are better able to deal with the pricing structure to achieve an optimal consumption level conditional on the pricing structure. Though the goal of the program may not have been achieved, better understanding of how households react to the block rate structure may

provide interesting insights into how to design block rate structures to achieve both equity and efficiency criterion.

Table 4: OLS and FE estimation of 2000-2005

	OLS		Fixed Effects	
Variable	coefficent	standard errors	coefficient	standard errors
Wsr	-0.265***	0.017	-0.246***	0.013
Wsr*Blockrate	0.458***	0.020	0.461***	0.015
wsrhouse	0.011***	0.004		
blockrate	-0.178***	0.004	-0.131***	0.003
ln(p1)	1.608***	0.036	1.050***	0.026
ln(p2)	-6.554***	0.086	-4.882***	0.061
ln(p3)	4.155***	0.058	3.084***	0.041
Restrict	-0.156***	0.002	-0.144***	0.001
2002	0.032***	0.002	0.018***	0.001
2003	0.066***	0.003	0.028***	0.002
2004	0.147***	0.006	0.102***	0.004
2005	0.136***	0.006	0.083***	0.004
Jan	0.106***	0.002	0.101***	0.001
March	-0.049***	0.002	-0.047***	0.001
April	-0.125***	0.002	-0.120***	0.002
May	0.131***	0.003	0.124***	0.002
June	0.385***	0.004	0.385***	0.003
July	0.293***	0.004	0.305***	0.003
August	0.313***	0.005	0.319***	0.003
Sept	0.271***	0.004	0.266***	0.003
Oct	0.102***	0.003	0.108***	0.002
Nov	0.006***	0.002	0.001	0.002
Dec	0.056***	0.002	0.038***	0.001
ln(blprddays)	0.180***	0.005	0.204***	0.004
avemaxt	0.021***	1e-8	0.021***	1e-8
totprecip	-0.030***	1e-8	-0.030***	1e-8
_cons	0.549***	0.019	0.433***	0.014
Obs	3,100,304		3,100,304	
r-squared	0.329		0.328	

*, **, *** denotes significance at the 10%, 5%, and1% levels respectively

Table 4: Instrumental Variables for WSR Households Only

	2S-FELS		2S-FELogit/FE		Fixed Effects	
Variable	coefficent	standard error	coefficient	standard error	coefficient	standard error
Wsr	-0.16008***	0.026008	-0.27008***	0.018366	-0.2576***	0.017032
Wsr*Blockrate	0.470563**	0.271943	0.384273***	0.033982	0.241175***	0.02393
blockrate	-0.5643*	0.35287	-0.40439***	0.047989	-0.22244***	0.037146
Obs	38099		38099		38099	
r-squared	0.4968		0.4982		0.4982	

*, **, *** denotes significance at the 10%, 5%, and1% levels respectively

Table 5: WSR Households above and below block boundaries

	Households Above		Households Below	
Variable	coefficent	standard error	coefficent	standard error
wsr	-0.035	0.037	0.045***	0.009
Obs	45925		554824	
r-squared	0.207		0.149	

*, **, *** denotes significance at the 10%, 5%, and1% levels respectively

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Appendix:

Proof of Proposition 1:

We know that w^{p*} solves:

$$\max_{w^p} u(w^p) + \int_{-\infty}^{\infty} v(M - \underline{p}w^a) f(w^a \mid w^p, b) dw^a$$

If the consumer is risk neutral than we can pass the expectation through the sub-utility function and have:

$$\max_{w^p} u(w^p) + v\left(\int_{-\infty}^{\infty} (M - \underline{p}w^a) f(w^a \mid w^p, b) dw^a \right)$$

We can now rewrite this as:

$$\max_{w^p} u(w^p) + v\left(M - \underline{p}(w^p + b)\right)$$

Taking the first order condition, we have:

$$u_w(w^p) = \underline{p}v_x(M - \underline{p}(w^p + b))$$

Since risk neutrality implies linear utility then $v_x(.) = \bar{v}_x$, a constant. So $u_w(w^p) = \underline{p}\bar{v}_x$, the same first order condition as in the certain case.

Proof of Proposition 2:

The first order condition is defined by:

$$u_w(w^{p*}) = \underline{p}\int_{-\infty}^{\infty} v_x(M - \underline{p}w^a) f(w^a \mid w^{p*}) dw^a$$

By assumption, $v_x(.)$ is a convex function, so by Jensen's inequality on convex functions, we know:

$$\underline{p}\int_{-\infty}^{\infty} v_x(M - \underline{p}w^a) f(w^a \mid w^{p*}) dw^a \geq \underline{p}v_x\left(\int_{-\infty}^{\infty} (M - \underline{p}w^a) f(w^a \mid w^{p*}) dw^a \right) = \underline{p}v_x(M - \underline{p}w^{p*})$$

Hence, $u_w(w^{p*}) \geq \underline{p}v_x(M - \underline{p}w^{p*})$.

Which implies that $u_w(w^{p*}) \geq u_w(w^*)$. So that $w^* \geq w^{p*}$. If $v_{xxx}(.) > 0$, then Jensen's inequality applies with a strict inequality and the result follows.

Proof of Corollary 1:

We outline the proof corresponding to the case when households underestimate their actual use. Note that a positive *b* simply shifts the distribution of actual water use to the right. Thus, for $b > 0$:

$$\int_{-\infty}^{z} f\left(w^a; w^p, b = 0\right) dw^a > \int_{-\infty}^{z} f\left(w^a; w^p, b > 0\right) dw^a$$

Under the assumption that $v_x \geq 0$ and $v_{x,x} \leq 0$ it follows that

$$\underline{p}\int_0^{\infty} v_x\left(M - \underline{p}w^a\right) f\left(w^a; w^p, b = 0\right) dw^a \geq \underline{p}\int_0^{\infty} v_x\left(M - \underline{p}w^a\right) f\left(w^a; w^p, b > 0\right) dw^a$$

Therefore $u_w\left(w_{b>0}^{p*}\right) \leq u_w\left(w_{b=0}^{p*}\right)$ and $w_{b>0}^{p*} \geq w_{b=0}^{p*}$.

Proof of Proposition 3:

If we suppress the price structure, we can write the consumer's problem under uncertainty as in (2.2):

$$\max_{w^p} u(w^p) + \int_{-\infty}^{\infty} v(M - c(w^a)) f(w^a \mid w^p, b) dw^a$$

Now, since preferences are risk neutral, we can rewrite this as:

$$\max_{w^p} u(w^p) + v\left(\int_{-\infty}^{\infty} M - c(w^a) f(w^a \mid w^p, b) dw^a\right)$$

Since preferences are risk neutral, we know $v_x(.) = \bar{v}_x$, a constant. Hence, we can rewrite the first order condition as:

$$u(\hat{w}^{p*}) = \underline{p}\bar{v}_x \int_{-\infty}^{\hat{w}} f(w^a \mid \hat{w}^{p*}) dw^a + \bar{p}\bar{v}_x \int_{\hat{w}}^{\infty} f(w^a \mid \hat{w}^{p*}) dw^a$$

Since $\bar{p} > \underline{p}$ then $u(\hat{w}^{p*}) > \underline{p}\bar{v}_x = u(\hat{w}^*)$. Hence, $\hat{w}^{p*} < \hat{w}^*$ because of the concavity of *u*.

Proof of Proposition 4:

The proof follows similarly to that of Proposition 3 and noticing that since $\bar{p} > \underline{p}$, $u(\hat{w}^{p*}) < \bar{p}\bar{v}_x = u(\hat{w}^*)$.

Proof of Proposition 5:

Starting from equation (2.13). As we saw in Proposition 2 the concavity of *v* alone causes consumer's to cut back.
That is, through Jensen's inequality we know that:

$$\underline{p}v_x\left(M - \underline{p}w^a\right) \leq \underline{p}\int_{-\infty}^{\infty} v_x\left(M - \underline{p}w^a\right) f\left(w^a; \hat{w}^{p*}\right) dw^a$$

The income effect associated with the IBR enhances this effect. Note that since $v_{x(\ )}$ is decreasing

$$v_x\left(M - \underline{p}w^a\right) < v_x\left(M - \underline{p}w^a + a\left(\hat{w} - w^a\right)\right) \ \forall w^a > \hat{w}$$

Therefore,

$$\underline{p}\int_{-\infty}^{\infty} v_x\left(M-\underline{p}w^a\right) f\left(w^a;\mathfrak{w}^{p*}\right)dw^a <$$

$$\underline{p}\int_{-\infty}^{\mathfrak{h}} v_x\left(M-\underline{p}w^a\right) f\left(w^a;\mathfrak{w}^{p*}\right)dw^a + \underline{p}\int_{\mathfrak{h}}^{\infty} v_x\left(M-\underline{p}w^a + a\left(\mathfrak{h}-w^a\right)\right) f\left(w^a;\mathfrak{w}^{p*}\right)dw^a$$

Finally, there is the risk of hitting the higher price. This is reflected above by $a\int_{\mathfrak{h}}^{\infty} v_x\left(M-\underline{p}w^a + a\left(\mathfrak{h}-w^a\right)\right) f\left(w^a;\mathfrak{w}^{p*}\right)dw^a$. When $a>0$, as is the case with an IBR, we know that this term is positive. Together these imply that $u_w\left(\mathfrak{w}^{p*}\right) > u_w\left(\mathfrak{w}^{*}\right)$ and hence, $\mathfrak{w}^{p*} \le \mathfrak{w}^{*}$.