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Municipal Water Prices as a Tool for Dynamic Adaptation to Climate Variability

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Abstract

Water utilities in the southwestern U.S. operate on a limited revenue stream, are expected to encourage water conservation, and are working with increasingly stressed water supplies. Expectations for increased temperatures and more frequent extreme weather events make it important for water utilities to be able to adapt operations and revenue streams to changing conditions. This article draws from multiple examples of strategic price-setting techniques used throughout different industries to encourage specific consumer behaviors and to control revenue outcomes. Using price-setting techniques seen in the electricity and airline industries, this article develops an iterative process for water utilities to strategically set prices for residential water use with the goal of promoting water conservation, stabilizing revenue and making it affordable for all users to meet their basic water needs.

1. Introduction

New understanding regarding the frequency and magnitude of extreme weather events under climate change, as well as volatile cycles in the national and regional economy, increases the financial vulnerability of water utilities (Moss, et al. 2013). Water utilities in the desert southwestern of the United States operate on a limited revenue stream, are expected to encourage water conservation and are working with increasingly stressed water supplies. Over the last several decades many water utilities have seen a decreasing trend in water consumption, making it increasingly difficult for utilities to generate sufficient revenue from their users. Though the decrease in consumption is a step toward increased conservation, the rapid rate at which consumption is decreasing makes it difficult for utilities to cover costs and maintain financial stability.

The Texas water utility, San Antonio Water System, has recognized the importance of rate setting to incentivize conservation and to ensure financial stability (Tiger, Hughes and Eskaf 2014). The San Antonio water provider has seen water use decrease steadily over the last 20 years with significant negative impacts on utility finances. It has adopted a policy of conducting a complete water rates study every five years. The Austin Water Utility in Austin, Texas is facing similar revenue issues. The long-term drought in the region has pushed the utility to implement watering restriction and conservation programs that reduce revenues and make it difficult for the utility to cover the costs of infrastructure updates (Tiger, Hughes and Eskaf 2014).

Westminster Colorado's water utility recently commissioned a study that showed its effective oriented pricing has promoted a 21% reduction in average per capita use over the past 30 years. This reduction has allowed the city to grow without the need for the utility to purchase additional water rights to meet demand, which in turn has avoided an estimated increase in water rates of 99% (Feinglas, Gray and Mayer 2013). One post-wild fire study performed in Flagstaff, Arizona showed that water users in the City of Flagstaff's water service area were willing to pay $4.89 per month on user water bills to reduce the risk of fire in their watershed (Mueller 2013). This result came after city residents saw the impacts of the extreme flooding events that followed a large 2010 fire that damaged water pipelines owned by the city water utility.

Water utilities are recognizing the value of price-setting techniques to adapt to changes in the physical and consumer climate of their utility. Tucson Water is a prime example of a water utility facing increased pressure under climate change. Tucson Water provides water to a population of about 709,000 people, through approximately 226,000 service connections within its service area. These customers consumed approximately 136,000 acre-feet (AF) of water in 2007. Tucson Water's estimated projections for the year 2020 expect demand to reach 175,000 AF. Though 2007 projections indicated that the utility should expect a total increase in consumption of about 29%, recent trends indicate that this projection may be inaccurate (Tucson Water 2009).

In addition to uncertainty over future demand of single family residential (SFR) users in Tucson, the water utility is also faced with uncertainty from its primary water source—the Colorado River. In 2007 16% of Tucson Water's supply came from non-renewable groundwater with a plan to be completely reliant on groundwater recharge from Colorado River water via its Central Arizona Project (CAP) allocation and local reclaimed water production. The movement from non-renewable groundwater supplies to a renewable supply coming from Arizona's allocation of the Colorado River is a movement toward a more resilient water supply in the future. Though the plan of a sustainable water source is a step in the right direction, changes in supply reliability due to the possible effects that climate change may have on the Colorado River's flows further complicates the idea of a water supply solely dependent on the Colorado River.

A recent summary published in the Bulletin of the American Meteorological Society notes that Colorado River stream flows are expected to decline by between 6% and 45% mid-century (Vano, et al. 2014). Additionally, the study shows that conservative estimates expect annual temperatures to rise by 3.6° ±1.8°F in the southwest, while precipitation is expected to decrease by 2.5% ±6%. The large range of expected stream flow and climate projections for the next 50 years shows how important it is for utility managers to address a wide range of outcomes. Having an understanding of how users will change water consumption patterns as a result in changing price allows water utility managers to set prices in a manner that can help operations adapt to the changes in the supply of water.

To understand how different types of users respond to price as well as climatic factors, this article uses a new demand model for water users in Tucson, Arizona to consider water provider revenue stabilization. In addition to discussing the different climatic variables that influence water demand, this article uses consumer response to price to inform price-setting practices. The estimated price response is used for different user segments to set prices in a way which promotes conservation, affordability, and revenue stability for water utilities. The demand models show that users are significantly responsive to changes in price and that prices for water can be used as an effective tool to promote conservation and revenue stability, two goals that can be difficult for a water utility to reconcile. The demand models also indicate that users are significantly responsive to changes in different weather factors such as temperature and precipitation.

The volatility expected in future precipitation events and temperatures for the Southwest and the user responsiveness to weather events makes it even more important for water utilities to adapt operations as climate conditions and user demand change. The increased occurrence of extreme weather events that accompanies climate change will only exacerbate the need for swift adaptation by water managers (Garfin, et al. 2014). The ability to adjust pricing structures precisely to reach revenue and conservation goals is a tool that will become increasingly valuable to influence user behavior. Using economic principles and user data, this article develops a process for setting water prices that helps water utilities reach revenue and conservation goals. The process outlined takes into account demand volatility and can be updated to ensure that each time a utility sets prices, the new pricing structure will address changing water utility concerns.

2. Literature Review

Over recent decades, urban water managers in the Southwest have seen residential water use decrease steadily. This decrease in per household use, as well as a decrease in overall water consumption in many cities, puts financial strain on water utilities who have invested in infrastructure anticipating increasing water use over time (Alliance for Water Efficiency 2012). Flawed long-term water demand estimates cause problems on both the cost and revenue sides of water utility operations. On the cost side, the capital intensive nature of delivering water forces utilities to invest in structures in order to meet the projected demand of their users. Since actual demand is decreasing, some utilities are operating well below their capital capacity. On the revenue side, lower than expected use and revenues result from decreasing consumption.

Though public water utilities are constrained by a zero-profit objective, they are expected to cover their operating costs from water-delivery revenues and other fees (Griffin 2006). Though water utilities use many different fees and surcharges to cover costs of operation, focusing on volumetric charges as assigned by an increasing block rate structure encourages user conservation and can help the utility achieve revenue stability (Donnelly, Christian-Smith and Cooley 2013). In order to design a pricing structure that is most effective at achieving a given goal set by water utilities, it is important for managers to understand how users respond to prices. Though the demand for municipal water is consistently found to be price inelastic, nearly every study in the water demand literature finds price response to be non-zero and statistically significant. The non-zero price response shows that setting prices has a measurable influence on how water users choose to consume.

In addition to prices influencing user consumption, user price responsiveness governs how a given price schedule affects revenue. Changing price affects revenue both directly and indirectly. The direct effect comes from the direct calculation of total revenue: if price is increased, ceteris paribus, total revenue will increase. The indirect effect of price changes on total revenue comes from the complication of lifting the ceteris paribus restriction. Because consumers make inter-related consumption decisions based on prices, an increase in the price of water will reduce the amount of water consumed (Hewitt and Hanneman 1998, Olmstead, Hanemann and Stavins 2007, Klawitter, Colby and Thompson 2014, Tiger, Hughes and Eskaf 2014). Having price elasticity of water demand estimates allows water utility managers to understand both the direct and indirect effects that a price change will have on revenue.

In recent years, there have been several reports discussing how price setting and knowledge of price elasticity for water demand can help utility managers reach revenue and conservation goals (Donnelly, Christian-Smith and Cooley 2013, Tiger, Hughes and Eskaf 2014, Alliance for Water Efficiency 2012). Though the reports discuss how prices can be useful, the literature is lacking in an explicit process that can be used by utility managers to set prices. In order to develop the process outlined in this article, examples were taken from other industry applications for setting prices. The airline industry and the electric utility industry, in particular, are good examples for drawing an analogy of how water utilities can effectively use prices to manage revenue issues (Phillips 2005).

To develop the clearest analogy for how water utilities can benefit from using price as a revenue management tool, it is useful to start with examples of targeted price-setting behavior from the electricity industry. Electric utilities give a good example of a similar business structure to that of a water utility (Albadi and El-Saadany 2008). Like water utilities, electric utilities are regulated natural monopolies, which have to adhere to government oversight on pricing (Phillips 2005). Like many water utilities, electric utilities often employ non-constant marginal pricing schemes to encourage appropriate user behavior. Many electric utilities find that strategic price-setting techniques can encourage conservation and successfully shift peak loads to off-peak times; in some cases reducing peak demand by 5% can reduce marginal costs to the utility by as much as 55% (Phillips 2005).

The focus on cost minimization (rather than revenue maximization) by electric utilities is a different issue than that of decreasing consumption over time, currently faced by water utilities in the Southwest. In the case of Tucson Water, the main variable cost of operations is the energy used for water delivery. Currently Tucson Water has an agreement which allows for electricity to be purchased at a constant per-unit wholesale price. In light of the expectation of climate variability, it would be unrealistic for water utilities to not expect energy prices to increase in the future. Given that electricity prices are a large portion of the cost of water deliveries, it will likely be necessary in the future for water utilities to set marginal prices for water in a way that encourages water use that helps offset the burden of increased energy costs.

The airline industry's current price-setting behavior serves as a closer analogy to the type of revenue issues that water utilities are facing. Airlines operate in a capital heavy industry that requires long-term planning to keep supply of flights at an optimal level with respect to demand. This requires airlines to project demand into the future and make sure they have an adequate fleet to service all of the determined flight paths (Jacobs, et al. 2012, Etschmaier and Mathaisel 1985). In the short-run business operations of an airline, the fleet size and flight schedules are fixed. Since the capacity allocation is determined for long-run operations based on projected demand, if demand decreases in the short run, the airline will lose revenue while costs stay relatively constant. The short-run decision for the airline is not one of minimizing costs, but maximizing revenue given the capital stock previously decided for long-run operations.

Though the long-run objective of a water utility can include promoting water conservation, in the short run the water utility must dance a fine line between promoting conservation objectives and generating enough revenue to cover costs (Ward and Pulido-Velazquez 2008). In a similar way to the airline example, the short-run operations of the water utility require managers to achieve a revenue goal that covers the cost of delivery, including the long-term fixed costs associated with capital investments.

One important revenue-maximizing tool used in the airline industry is dynamic pricing, which allows the airline to capture consumers' maximum willingness to pay in different market segments (Phillips 2005). The airline industry has long been a user of multiple pricing levels for different seats on the same leg of an airline flight based on a multitude of spatial and temporal variables (Brumelle and McGill 1993).

Airlines are able to segment their users according to their purchasing behavior and use price responses for different market segments to optimize revenue (Phillips, 2005). Through the process of price segmentation, airlines must find a price that entices enough passengers to purchase tickets to keep planes as close to capacity as possible, while keeping prices high enough to minimize the crowding-out effect of early bird travelers. If the prices are too low, the direct price effect on revenue will be too weak to achieve optimal revenue. In other words, every plane will be full of early-bird ticket purchasers and the airline will miss out on the higher revenues that would come from the higher priced tickets purchased at a later time. If tickets are priced too high, the indirect price effect on revenue will push consumption to a sub-optimal level (Brumelle and McGill 1993).

Water utilities can optimize their revenues using a similar type of price setting and market segmentation to the one used by the airline industry. Though the cost and revenue issues between the airline industry and municipal water industry are similar, the pricing incentive structures implemented by water utilities are different from those used by airlines. The increasing block rate structures previously discussed are already in place in many water utilities in the southwestern U.S.

The increasing block rate structure allows water users to segment themselves into the desired price range they are willing to pay (Olmstead, Hanemann and Stavins 2007, Hewitt and Hanneman 1998). Using this self-selection process and the coinciding price elasticities for each segment, prices can be set in a way that not only achieves a desired revenue goal, but also can take into account water conservation goals. Goals in price setting for a water utility should include setting prices high enough to encourage water conservation and ensure financial stability for the water utility. At the same time, price setting needs to keep prices low enough that water users from all socio-economic backgrounds can afford to buy the quantity of water that meets their essential water use needs.

3. Price-Setting Process

Water utilities are expected to set prices for water in a way that not only covers cost of delivery, but also encourages conservation and keeps basic water service affordable to all users. This section uses the demand schedules estimated for four residential water user segments in Tucson Water's service area to examine revenue optimization. The four demand estimates are based on samples of representative users of the four user segments in Tucson Water's increasing block rate structure. Table 1 shows the number of users in Tucson Water's service area that are in each segment. A full description of the user segmentation protocol is provided in Residential Water Demand Management: Examples of User Segmentation in Tucson, Arizona (Klawitter, Colby and Thompson 2014).

[Insert Table 1 about here]

The four demand models were estimated using random-effects panel regression models with data covering a sample period of 48 months and a cross-section of users sampled from the population of single family residential users in the Tucson Water service area. The simplified demand models shown in Table 2 represent the results of multivariate random effects model (Klawitter, Colby and Thompson 2014). The demand models control for weather, demographic, and home characteristics to provide precise demand estimates for the sample period. The simplified demand equation (with demand written only as a function of price) was obtained by using the mean summer value for each independent variable in the model to obtain a single intercept.

The example chosen for this article shows price setting using summer month demand curves. Summer is the peak season for water use and the season most straining on system capacity. As regional temperatures increase and heat waves become more frequent and severe, summer water provision will be further stressed due to increases in water demand related to providing more electricity for cooling homes and businesses, as well as higher water needs for crops and landscape. Though revenue is only considered for summer months, a utility should adjust demand curves for winter, spring, and fall to get the most accurate annual revenue projections for a given price structure.

Using the price-quantity relationships shown in Figure 1, it is possible to solve for a price for each user segment which will optimize total revenue. Tucson Water operates under capacity constraints related to both supply availability and system capacity and so it is reasonable to think of the revenue optimization process as a constrained optimization problem. Though it is possible to solve the system of equations using mathematical programming, the iterative process outlined in this article is preferable because it allows utility managers to set prices while considering affordability and political climates, rather than simply solving for the price value that maximizes revenue. Table 2 shows the estimated demand equations for each of the corresponding user segments that will be used in the revenue optimization process.

[Insert Table 2 about here]

We develop an iterative process for setting individual block prices that allows for prices of upper tiers to be set while accounting for changes to user willingness to pay that occur due to the lower price paid for water in all preceding blocks. The iterative process first sets the price for Block 1, and then adjusts the demand curves for all upper tier user segments before setting the prices for Block 2. This process is repeated for each block so that prices set for each block take into account the consumer surplus gained from the lower marginal price from each of the lower blocks. The iterative price-setting process for Blocks 1 and 2 is outlined in the remainder of this section. The complete price-setting process for all four blocks and the procedure for adjusting demand is outlined in Appendix 1 and Appendix 2 respectively.

Before outlining the revenue optimization process, it is important to note that the goal of this process is to set prices to “optimize” revenue for Tucson Water, not just to maximize revenue. In this case, revenue optimization refers to setting prices to allow Tucson Water to meet its goals of affordability for low and fixed-income customers, covering costs and conservation. The numbered list below shows a brief summary of the steps of the price-setting procedure outlined in the remainder of this article.

Step 1: Superimpose estimated average demand curves on the existing increasing block price structure. If a given block's demand curve does not intersect that block's marginal price, reduce the threshold for the block sufficiently that the average demand curve intersects the newly defined block.

Step 2: Beginning with the lowest block (Block 1), set the marginal price for Block 1 with affordability in mind.

Step 3: Adjust Block 2's demand curve to reflect new MP1. Then set the marginal price of Block 2 to meet either revenue maximization or conservation (or both) goals.

Step 4: Repeat Step 3 successively for Block 3 and all successive blocks in IBR schedule.

The first step in the revenue optimization process is to examine the thresholds for each of the four blocks. Figure 1 shows quantity-price relationship for each of the four user segments during the summer months of the sample period. Even with the stringent market segmentation performed by Klawitter, Colby and Thompson (2014), the demand curves for Segments 3 and 4 show that even if prices were set to zero, the average user would not be expected to consume enough water to see the price of water for respective blocks. The lower-than-block-threshold use by Segments 3 and 4 is a result of Tucson Water not adjusting block thresholds over time as water use decreased. This indicates that the thresholds between blocks are not set to effectively incentivize user behavior in the upper tiers. Consequently we recommend that the thresholds for each of the segments be set to 10 CCF increments.

[Insert Figure 1 about here]

Block increments of 10 CCF cause the demand curve for each of the segments to fall within the appropriate block and therefore allow the representative users for each segment to receive the price signals from the marginal price corresponding to their block. Adjusting the block thresholds also allows prices for each block to be set using observed user response. Applying the new 10 CCF threshold for the four blocks results in a) Block 1=0-10 CCF, b) Block2= 11-20 CCF, c) Block 3= 21-30, and d) all consumption over 30 CCF being charged at a rate for Block 4. The new 10 CCF threshold is employed for the remainder of this optimization process.

4. Price-Setting and Revenue Generation for Block 1

Because municipal water is used by all residents in the city, regardless of income, the goal in setting the price for Block 1 is primarily targeted to meet the affordability goal of Tucson Water, so that all households have access to water to cover their basic needs at the relatively low costs the utility has applied in recent years. Figure 2 (a) shows the total revenue curve for Segment 1 users as well as the 95% confidence interval for total revenue, and Figure 2 (b) shows the demand curve for Segment 1 users as well as the 95% confidence interval for demand based on estimated price response. Looking at the two graphs simultaneously allows the price setter to see how average prices in Block 1 will affect both quantity consumed by Segment 1 users as well as the resulting revenue generated. The confidence bands about the total revenue curve were generated using the confidence interval for the estimated price response for Segment 1 users; the steps for calculation of the confidence intervals are shown in Appendix 3.

[Insert Figure 2 about here]

For this exercise, Block 1 average price was set equal to the real average price of water for Block 1 during the sample period, which is approximately equal to $2. Given the average price of $2, Segment 1 users are expected to consume an average of 7.39 CFF (±.3CCF) during the summer months. The resulting expected total revenue from an average price set at $2.00 is $14.79 (±$0.60) per month, during the summer months. Since Tucson Water sets a marginal price schedule, it is also important to see what the marginal price for water should be set at for Block 1. In order to calculate the marginal price for Block 1, a monthly service surcharge of $5.68 was assumed, which is the real average value of the connection surcharge for a typical 5/8" water meter in the Tucson Water service area during the sample period. Equation 1 shows how the marginal price for Block 1 was obtained from the average price (If a utility employs multiple surcharges, Equation 1 should be adapted to include all surcharges).

$$AP_{block_1} = \frac{Surcharge + MP_1 \times {Q_1}^*}{{Q_1}^*} \tag{1}$$

Algebraic manipulation gives the marginal price for Block 1, shown in Equation 2.

$$MP_1 = AP_{block_1} - \frac{Surcharge}{{Q_1}^*} \tag{2}$$

Using the surcharge of \$5.68, the average price for Block 1 of \$2, and the resulting quantity of water consumed of 7.39 CCF, the marginal price for Block 1 is easily calculated. The resulting value for MP_1 is equal to \$1.23. It is important to note that an average price of \$2 is far from the revenue-maximizing average price of \$12.50, but this rate allows the low water consumers in Segment 1 to purchase water at a rate low enough to meet the affordability objective of Tucson Water.

Once the marginal price for Block 1 is set, it is used to adjust the demand curves for each of the three higher-tier user segments. The adjusted demand curve for each segment, conditional on the connection surcharge and all marginal prices for lower blocks, is calculated for each successive user segment once the block price for each lower block is set. The adjusted demand curve is henceforth referred to as the conditional demand curve; the process for obtaining the conditional demand curves is outlined in Appendix 2.

5. Price Setting and Resulting Revenue for Block 2

In order to calculate the conditional demand for Block 2, the total cost for all water consumed by Segment 2 users in Block 1 must be calculated. Because Segment 2 users are assumed to consume in Block 2, it is assumed that Block 2 users will consume all 10 CCF available at the Block 1 marginal price of \$1.23. The calculation of the conditional demand curve for Segment 2 users is shown in Appendix 2a. The resulting total revenue curve for consumption in Block 2, the conditional demand curve for Segment 2, and their 95% confidence intervals are shown in Figures 3 (a) and (b) respectively.

[Insert Figure 3 about here]

The conditional demand and total revenue curves respectively show the relationship between marginal price and Block 2 consumption and between marginal price and Block 2 revenue. Given the conditional demand for Block 2, it is reasonable to set the marginal price for water consumed in Block 2 anywhere between $1.24 (must be more than $1.23 to be an IBR) and a revenue maximizing price of $13. If affordability is more of a concern to utility managers at the time of price-setting, Block 2 prices should be set closer to $1.23 than $13. If conservation and covering capital costs are more of a concern at the time of price setting, the utility should set the marginal price for Block 2 closer to $13, but never more than $13.

For this exercise, the marginal price for Block 2 consumption is set at $6, because it is an increase in price from the previous year, but a small enough change that it is considered to be realistic given past price-setting behavior of Tucson Water (though, Figure 3 does show that increasing the marginal price past $6 per unit would increase revenue further). At a marginal price of $6 the expected Block 2 consumption from Segment 2 users is expected to be 7.47 CCF (±.22 CCF) during the summer months. The expected total revenue from Block 2 consumption from Segment 2 users is $44.87 (±$1.33). The expected total consumption for Segment 2 users is 17.47 with expected total revenue for all water consumed during the summer months equal to $62.85 (±$1.33).

Figure 4 shows the increasing block rate structure produced by the price-setting procedure previously outlined compared to the actual price schedule implemented by Tucson Water during the 2010-2011 fiscal year. Table 3 shows the prices for each of the increasing block rate schedules depicted in Figure 4, along with the percentage change in price between the two.

[Insert Figure 4 about here]

[Insert Table 3 about here]

Table 4 includes the expected revenue of an average customer for each segment during the summer months, calculated using the same procedure outlined in Appendix 1 and using the observed prices from fiscal year 2010-2011. Table 5 shows the expected per household consumption for each segment during the summer months of the sample period. Table 5 is broken into two expected consumption values, expected consumption under the proposed pricing structure, and the average consumption for FY 2010-2011.

[Insert Table 4 about here]

[Insert Table 5 about here]

Using the information shown in Tables 4 and 5 and the number of households in each segment shown in Table 1, the aggregated expected total revenue for SFR users is calculated. Tables 6 and 7 show the aggregate expected total revenue and total use for SFR users in the Tucson Water Service area during the summer months of the sample period. The aggregation of expected values for all SFR users is found for each segment by multiplying usage and revenue values by the number of households in each segment as shown in Table 1.

Because the number of households in each segment constitutes about 98% of the population of SFR water users (due to sampling process to obtain balanced panel), the aggregated values are under-estimates of total use and total revenue. Considering that the households were segmented using the probability distribution of the population of households during the sample period, the proportion of revenue attributed to each segment should be accurate.

[Insert Table 6 about here]

[Insert Table 7 about here]

The “Total” row of Tables 6 and 7 shows total expected revenue and total expected use for the SFR users for an average summer month during the sample period. Changing the marginal price of each block to the rates shown in Figure 4 decreases expected consumption by 5% (68,147 CCF) per average summer month for all SFR users during the sample period. The proposed pricing structure also increases the aggregate expected total revenue from SFR users by 20% ($870,177).

The use and revenue estimates shown in Tables 6 and 7 are accurate with a 95% level of significance with respect to prices. In order to focus on price, we assume that all other explanatory variables take on the mean values for the sample period. In order for water utilities to have the most comprehensive estimates of use and revenue, it would be important for the utility to perform sensitivity analysis on the demand curves with respect to different independent variables, such as weather variables. Performing sensitivity analysis for different seasons would allow the water utility to get the most precise usage and revenue projection possible for a given pricing structure.

6. Conclusions

Facing climate and economic volatility, many utilities in the southwestern United States are experiencing decreasing water use and are having trouble covering their capital and operating costs. Increased costs, and increased variance in costs, are likely as utilities confront higher temperatures and greater frequency of drought, flood, heat waves, and wildfire. This article shows how an increasing block rate structure can be adapted by a water utility to stabilize revenues while also accomplishing equity and conservation goals. We demonstrate how block thresholds and marginal prices can be set in a way that targets specific user segments and encourages conservation.

Using estimated demand schedules and price responsiveness of users to set prices can help water utilities achieve revenue goals in the short run and give managers the added benefit of seeing how changes in price will affect water use at both the household and at the aggregate level. The 20% increase in revenue and 5% decrease in total household consumption from the recommended change in prices show that prices can be an effective tool for water utilities to encourage water conservation and to control revenue outcomes.

As water supplies become increasingly stressed with climate change it will become more important for utility managers to understand how users will respond to changes in prices. Using demand estimations and revenue curves allows utilities to set prices with precision to adapt to changes in water supply availability and system capacity limitations. In addition, this tool sets prices in a precise way, which will allow utility managers to increase revenues when it is necessary to recoup losses to infrastructure following extreme weather events such as forest fires and flooding. The tool will also be helpful for utilities to adapt conservation plans in the event of changes in user behavior resulting from increased temperatures and variability in precipitation events. The addition of sensitivity analysis to demand models gives utility managers the most accurate projections for revenues resulting from a given pricing structure.

Appendix 1: Price-setting Process

Appendix 1a: Price Setting and Resulting Revenue for Block 3

The same consumption assumption that was used for Segment 2 is reassigned for Segment 3 users regarding usage in Blocks 1 and 2—Segment 3 users are assumed to consume all 20 CCF at the given marginal prices for Blocks 1 and 2 and given the connection surcharge of $5.68. The calculation of the conditional demand curve for Segment 3 users is shown in Appendix 2b. The resulting total revenue curve for consumption in Block 3, the conditional demand curve for Segment 3, and their 95% confidence intervals are shown in Figures 5 (a) and (b) respectively.

[Insert Figure 5 about here]

The conditional demand curve and corresponding total revenue curves show the relationship between expected quantity consumed and marginal price for Block 3 and expected total revenue and marginal price for Block 3 respectively (See Appendix 2b). Given the conditional demand for Segment 3 it is reasonable to set the marginal price for water consumed in Block 3 anywhere between $6.01 (must be more than $6.01 to be an IBR) and a revenue-maximizing price of $28. The same rational for affordability versus conservation discussed in Section 5.3b holds here.

For this exercise, the marginal price for Block 3 consumption is set at $9.50, with expected Block 3 consumption from Segment 3 users of 6.87 CCF (+.2/-.06 CCF) during the summer months. The expected total revenue from Block 3 consumption from Segment 3 users is $65.32 (-$1.84/+$0.62). The expected total consumption for Segment 3 users is 26.87 CCF

(+.2/-.06 CCF) with expected total revenue for all water consumed during the summer months equal to $143.30 (-$1.84/+$0.62).

Appendix 1b: Price setting and resulting revenue for block 4

Repeating the same price-setting process as used for Blocks 2 and 3, the calculation of the conditional demand curve for Segment 4 users is shown in Appendix 2(c). The resulting total revenue curve for consumption in Block 4, the conditional demand curve for Segment 4, and their 95% confidence intervals are shown in Figure 6 (a) and (b) respectively.

[Insert Figure 6 about here]

The conditional demand curve and corresponding total revenue curves show the relationship between expected quantity consumed and marginal price for Block 4 and expected total revenue and marginal price for Block 4 respectively (See Appendix 2(c)). Given the conditional demand for Segment 4, it is reasonable to set the marginal price for water consumed in Block 4 anywhere between $9.51 (must be more than $9.50 to be an IBR) and a revenue-maximizing price of $83.50.

For this exercise, the marginal price for Block 4 consumption is set at $15.00, with expected Block 4 consumption from Segment 4 users of 8.01 CCF (+.08/-.3 CCF) during the summer months. The expected total revenue from Block 4 consumption from Segment 4 users is $120.07 (+$0.77/-$2.88). The expected total consumption for Segment 4 users is 38.01 CCF (+.08/-.3 CCF) with expected total revenue for all water consumed during the summer months equal to $293.05 (+$0.77/-$2.88).

Appendix 2: Conditional Demand and Total Revenue Curve Calculation by Segment

This appendix outlines the mathematical justification of the calculation of the conditional demand curves and corresponding total revenue curves for Segments 2, 3, and 4. Conditional demand curves are the demand curves for each upper tier user segment, conditional on the connection surcharge and the marginal price for each preceding block. It is important to note that the demand curves estimated in this thesis are in a semi-log form. This means that the natural logarithm of usage is the dependent variable, while the un-adjusted average price was used as the explanatory price variable. The calculations in Appendices 2 (a) through 2 (c) are all completed in the semi-log scale before being translated to price per CCF and CCF.

Appendix 2a: Conditional Demand and Total Revenue for Block 2

Recall from section 5.3a, the marginal price for water consumed in Block 1 is set at \$1.23 per CCF with a connection surcharge of \$5.68. Because Segment 2 users are expected to consume in Block 2, it is assumed that Segment 2 users will consume all 10 CCF available at the Block 1 marginal price before having to make any consumption decision based on Block 2 prices. To adjust the Segment 2 user unconditional demand, D_u, to conditional demand, D_c, the area under the unconditional demand curve is first calculated. Since this is a linear demand function, the area under the D_u can be calculated using simple geometry. The area under D_u represents the total willingness to pay for water for Segment 2 users. In order to adjust D_u to conditional demand, the total cost of water consumed in Block 1, including the connection surcharge must be subtracted from the area under D_u. Doing so accounts for the benefits to Segment 2 users gained from paying a lower price for water consumed in Block 1.

$D_{u\ seg.2}$=P=28.1-9.1lnQ

Price intercept=28.1

lnCCF intercept= $\frac{28.1}{9.1}$ =3.09

Area $D_{u\ seg.2}$= $\frac{Price\ intercept\ \times lnCCF\ intercept}{2}$ = \$43.27

Area $D_{u\ seg.2}$= $\frac{\$26.81\times 3.09}{2}$ = \$43.27

The average price of water consumed in Block 1, including connection surcharges is calculated below. The calculated average price is used to calculate the total cost of water consumed in Block 1 for Segment 2 users and is represented by the crosshatched box in Figure 7. The box represents the amount of consumer surplus that must be removed to shift the consumer from the unconditional demand curve to the demand curve conditional on lower block prices in previous blocks.

AP_{Block_1}=$\frac{\$1.23\times 10+\$5.68}{10}$ =\$1.80

TC_{Block_1}=\$1.80 x ln(10) = \$4.14

[Insert Figure 7 about here]

In addition to subtracting the total cost of water consumed in Block 1 to account for the benefits gained by upper tier users resulting from a lower marginal price for water in lower blocks, it is important to adjust the intercept on the ln(CCF) axis. This adjustment is necessary since the unconditional demand curves for Segment 2 users imply that the average user would not consume more than $e^{\ln(3.09)}$=21.97 CCF even if prices were set at zero. Adjusting the price ln(CCF) intercept to account for the 10 CCF obtained in Block 1 results in a new intercept for conditional demand D_c of ln(21.97-10)=2.48. Adjusting the ln(CCF) intercept in this way results in a new price intercept and slope for Segment 2 Demand, i.e., the Segment 2 conditional demand D_c. Calculation of the new price intercept and slope come from algebraic manipulation of the geometric calculation of Segment 2 willingness to pay above. The calculated conditional demand curve for Segment 2 is shown in figure 7.

Area $D_{c\ seg.2}$= Area $D_{u\ seg.2}$- TC_{Block_1}

Area $D_{c\ seg.2}$ =\$43.27-\$4.14 = \$39.13

Using the new ln(CCF) intercept and calculated area under the conditional demand curve, the new price intercept and slope of D_c can be calculated in the following way:

Area $D_{c\ seg.2}$= $\frac{Price\ intercept\ \times lnCCF\ intercept}{2}$ =\$39.13

$$\$39.13 = \frac{Price\ intercept\ \times 2.48}{2} \rightarrow Price\ intercept = \frac{\$29.13\times 2}{2.48} = \$31.81$$

$$Price\ intercept = \$31.81$$

Slope **$D_{c\ seg.2}$** = $\frac{-30.06}{2.48}$ = -12.82

Therefore:

$$\boldsymbol{D_{c\ seg.2}} = P = 31.81 - 12.82lnQ$$

[Insert Figure 8 about here]

Finding the inverse of this new conditional demand function and adjusting the quantity scale from ln(CCF) to CCF allows for calculation of conditional demand and the subsequent total revenue curves dependent on price. The inverse of the conditional demand function and calculation of total revenue is completed in the following manner:

$$D_{c\ seg.2} = P = 31.81 - 12.82lnQ \quad \rightarrow \quad lnQ = 2.48 - .08p.$$

To adjust from ln(CCF) to CCF, the exponential function e^x is applied to the conditional demand equation:

$\boldsymbol{D_{c\,seg.2}} = Q_{segment\ 2} = e^{(lnQ)} = e^{(2.48-.08p)}$.

Using this demand equation, the total revenue for consumption in Block 2 by Segment 2 users is calculated as

$TR = MP_{Block\ 2}\ x\ Q_{Segment\ 2} = MP_{Block\ 2} \times e^{(2.48-.08MP_{Block2})}$.

It is important to note that since the total cost of water consumed in all lower blocks, including surcharges has already been taken into account in the conditional demand equation, the new unit of measurement for price on the conditional demand and total revenue for Segment 2 is a marginal price value.

The confidence intervals for the Segment 2 conditional demand curve and subsequent total revenue curves were calculated in the same fashion as the conditional demand and total revenue curve for Segment 2 users. The adjustment for the confidence interval was done so based on the confidence interval about the estimated price response and is outlined in Table 8 of Appendix 2. Table 8 below shows the calculated equations for the confidence interval above and below the conditional demand curve for Segment 2 users.

[Insert Table 8 about here]

Appendix 2b: Conditional Demand and Total Revenue for Block 3

Following the same procedure outlined in Appendix 2a, this section outlines the calculation of the conditional demand curve for Segment 3 users, adjusted for the connection surcharge and the marginal price for Blocks 1 and 2.

Recall:

- Connection Surcharge=$5.68

- MP_{Block1}=$1.23
- MP_{Block2}=$6.00

The estimated unconditional demand curve for Segment 3 users is as follows:

$D_{u\ Seg.3}$=P=48.57-14.29lnQ

Price intercept=$48.57

lnCCF intercept= $\frac{48.57}{14.29}$ =3.39

Area D_u= $\frac{Price\ intercept\ \times lnCCF\ intercept}{2}$ = $82.33

Area D_u= $\frac{\$48.57\times 3.39}{2}$ = $82.33

The average price of water consumed in Blocks 1 and 2, including connection surcharges, is calculated below. The calculated average price is used to calculate the total cost of water consumed in Blocks 1 and 2 for Segment 3 users and is represented by the crosshatched box in Figure 8 below.

$AP_{Blocks\_1\&2}$=$\frac{\$6.00\times 10+\$1.23\times 10+\$5.68}{20}$ =$3.90

TC_{Block_1}=$3.90 x ln(20) = $11.68

[Insert Figure 9 about here]

Ln(CCF) Intercept= ln(29.96-20)=2.29

Area $D_{c\ seg.3}$= **Area $D_{u\ seg.3}$**- **$TC_{Blocks1\&2}$**

Area $D_{c\ seg.3}$=$82.33-$11.98 = $70.65

Using the new ln(CCF) intercept and calculated area under the conditional demand curve, the new price intercept and slope of D_c can be calculated in the following way:

Area $D_{c\ seg.3}$= $\frac{Price\ intercept\ \times lnCCF\ intercept}{2}$ =$70.65

$\$70.65 = \frac{Price\ intercept\ \times 2.29}{2}\ \rightarrow Price\ intercept = \frac{\$70.65\ \times 2}{2.27} = \$62.25$

$Price\ intercept = \$62.25$

Slope $D_{c\ \mathbf{seg.3}}$ = $\frac{-62.25}{2.27}$ = -27.42

Therefore:

$\boldsymbol{D}_{\boldsymbol{c}\ \mathbf{seg.3}} = P = 62.25 - 27.42lnQ$

The calculated conditional demand curve for Segment 3 is shown in Figure 9.

[Insert Figure 10 about here]

Finding the inverse of this new conditional demand function and adjusting the quantity scale from ln(CCF) to CCF allows for calculation of conditional demand and the subsequent total revenue curves dependent on price. The inverse of the conditional demand function and calculation of total revenue is completed in the following manner:

$D_{c\ seg.3} = P = 62.25 - 27.42lnQ \quad \rightarrow \quad lnQ = 2.27 - .036p$

To adjust from ln(CCF) to CCF, the exponential function e^x is applied to the conditional demand equation:

$\boldsymbol{D}_{\boldsymbol{c\ seg}.\mathbf{3}} = Q_{segment\ 3} = e^{(lnQ)} = e^{(2.27 - .036MP_{block3})}$

Using this demand equation, the total revenue for consumption in Block 3 by Segment 3 users is calculated as

$TR = MP_{Block\ 3}\ x\ Q_{Segment\ 3} = MP_{Block\ 3} \times e^{(2.27 - .036MP_{Block3})}$

The confidence intervals for the Segment 3 conditional demand curve and subsequent total revenue curves were calculated in the same fashion as the conditional demand and total revenue curve for Segment 3 users. The adjustment for the confidence interval was done so based on the confidence interval about the estimated price. Table 9 below shows the calculated equations for the confidence interval above and below the conditional demand curve for Segment 3 users.

[Insert Table 9 about here]

Appendix 2c: Conditional Demand and Total Revenue for Block 4

Following the same procedure outlined in Appendix 2a, this section outlines the calculation of the conditional demand curve for Segment 3 users, adjusted for the connection surcharge and the marginal price for Blocks 1, 2, and 3.

Recall:

- Connection Surcharge=$5.68
- MP_{Block1}=$1.23
- MP_{Block2}=$6.00
- MP_{Block3}=$9.50

The estimated unconditional demand curve for Segment 3 users is as follows:

$D_{u\ Seg.4}$=P=122.7-33.3lnQ

Price intercept=$122.7

lnCCF intercept= $\frac{122.7}{33.3}$ =3.68

Area $D_{u\ Seg.4}$= $\frac{Price\ intercept \times lnCCF\ intercept}{2}$ = $226.06

Area $D_{u\ Seg.4}$= $\frac{\$122.7 \times 3.68}{2}$ = $226.06

The average price of water consumed in Blocks 1, 2, and 3, including connection surcharges is calculated below. The calculated average price is used to calculate the total cost of water consumed in Blocks 1, 2, and 3 for Segment 4 users and is represented by the crosshatched box in Figure 10.

$AP_{Blocks\_1,2\&3}=\frac{\$6.00\times10+\$1.23\times10+\$9.50\times10+\$5.68}{30}=\$5.77$

$TC_{Blocks\_1,2\&3}=\$5.77 \times \ln(30) = \$19.62$

[Insert Figure 11 about here]

Ln(CCF) Intercept= ln(39.65-30)=2.26

Area $D_{c\ seg.4}$= Area $D_{u\ seg.3}$- $TC_{Blocks1\&2}$

Area $D_{c\ seg.4}$=\$226.06-\$19.62 = \$206.44

Using the new ln(CCF) intercept and calculated area under the conditional demand curve, the new price intercept and slope of D_c can be calculated in the following way:

Area $D_{c\ seg.4}$ $=\frac{Price\ intercept\ \times lnCCF\ intercept}{2}=\$206.44$

$$\$182.69 = \frac{Price\ intercept\ \times 2.26}{2} \rightarrow Price\ intercept = \frac{\$182.69\times 2}{2.26} = \$182.69$$

$$\boldsymbol{Price\ intercept} = \$182.69$$

Slope $D_{c\ seg.4}$ $= \frac{-62.25}{2.27} = -80.84$

Therefore:

$$\boldsymbol{D_{c\ \mathrm{seg.4}}} = P = 182.69 - 80.84lnQ$$

[Insert Figure 12 about here]

Finding the inverse of this new conditional demand function and adjusting the quantity scale from ln(CCF) to CCF allows for calculation of conditional demand and the subsequent total revenue curves dependent on price. The inverse of the conditional demand function and calculation of total revenue is completed in the following manner:

$D_{c\ seg.4} = P = 182.69 - 80.84lnQ \quad \rightarrow \quad lnQ = 2.26 - .012p$

To adjust from ln(CCF) to CCF, the exponential function e^x is applied to the conditional demand equation:

$\boldsymbol{D_{c\ seg.4}} = Q_{segment\ 4} = e^{(lnQ)} = e^{(2.26 - .012MP_{block4})}$

Using this demand equation, the total revenue for consumption in Block 2 by Segment 2 users is calculated as

$TR = MP_{Block\ 4}\ x\ Q_{Segment\ 4} = MP_{Block\ 4} \times e^{(2.27 - .036MP_{Block4})}$

The confidence intervals for the Segment 4 conditional demand curve and subsequent total revenue curves were calculated in the exact same fashion as the conditional demand and total revenue curve for Segment 4 users. The adjustment for the confidence interval was done so based on the confidence interval about the estimated price response. Table 10 below shows the calculated equations for the confidence interval above and below the conditional demand curve for Segment 4 users.

[Insert Table 10 about here]

Appendix 3: Calculation of Confidence Interval about Total Revenue Curves

Using the estimated demand curves and their respective confidence intervals and converting the natural log scale into the original consumption scale (CCF), the unconditional demand curves for each segment are adjusted by using the confidence interval about the price coefficient. The 95% confidence bands about the unconditional demand curves are then used to obtain the confidence bands for the conditional demand curves and the total revenue curves for each segment, shown in Table 11.

[Insert Table 11 about here]

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Tables:

Table1: Number of Households by Segment

Number of households by usage segment	
Block Segment	**Number of households**
Segment 1	85,620
Segment 2	21,136
Segment 3	7,116
Segment 4	5,078

Table 2: Estimated Demand Equations by Segment

User Segment	**Estimated Demand Equation**	**Fixed Block Thresholds**
Segment 1	$\ln Q_1=2.16-.08p_1$	0-15 CCF
Segment 2	$\ln Q_2=3.09-.11p_2$	15-30 CCF
Segment 3	$\ln Q_3=3.4-.07p_3$	30-45 CCF
Segment 4	$\ln Q_4=3.68-.03p_4$	≥ 45 CCF

Table 3: Marginal price by block and percentage change in marginal price

	Proposed Pricing	**FY 2010-2011 Pricing**	
Block Segment	**Marginal Price**	**Marginal Price**	**% Change in Price**
Block 1	$1.23	$1.54	**-20%**
Block 2	$6.00	$5.75	**4%**
Block 3	$9.50	$8.14	**17%**
Block 4	$15.00	$11.31	**33%**

Table 4: Expected summer month revenue per household by Segment

	Proposed Pricing		**FY 2010-2011 Pricing**	
	Connection Surcharge=$5.68		Connection Surcharge=$5.62	
Block Segment	**Marginal Price**	**Total Revenue**	**Marginal Price**	**Total Revenue**
Block 1	$1.23	**$14.74**	$1.54	**$15.76**
Block 2	$6.00	**$62.85**	$5.75	**$55.83**
Block 3	$9.50	**$143.30**	$8.14	**$114.57**
Block 4	$15.00	**$293.05**	$11.31	**$174.56**

Table 5: Expected summer use per household by Segment

	Proposed Pricing		**FY 2010-2011 Pricing**	
Block Segment	**Marginal Price**	**Expected Use**	**Marginal Price**	**Expected Use**
Block 1	$1.23	**7.39 CCF**	$1.54	**7.29 CCF**
Block 2	$6.00	**17.47 CCF**	$5.75	**20.23 CCF**
Block 3	$9.50	**26.87 CCF**	$8.14	**29.93 CCF**
Block 4	$15.00	**38.01 CCF**	$11.31	**37.34 CCF**

Table 6: Aggregated expected total revenue by Segment for summer

	Proposed Pricing		**FY 2010-2011 Pricing**	
	Connection Surcharge=$5.68		Connection Surcharge=$5.62	
Block Segment	**Marginal Price**	**Total Revenue**	**Marginal Price**	**Total Revenue**
Block 1	$1.23	**$1,262,038**	$1.54	**$1,349,371**
Block 2	$6.00	**$1,328,397**	$5.75	**$1,180,023**
Block 3	$9.50	**$1,019,723**	$8.14	**$815,280**
Block 4	$15.00	**$1,488,108**	$11.31	**$886,415**
Total		**$5,098,266**		**$4,228,089**

Table 7: Expected summer use per household by Segment

	Proposed Pricing		FY 2010-2011 Pricing	
Block Segment	**Marginal Price**	**Expected Use**	**Marginal Price**	**Expected Use**
Block 1	$1.23	**632,732 CCF**	$1.54	**624,170 CCF**
Block 2	$6.00	**369,246 CCF**	$5.75	**427,581 CCF**
Block 3	$9.50	**191,206 CCF**	$8.14	**212,982 CCF**
Block 4	$15.00	**193,014 CCF**	$11.31	**189,612 CCF**
Total		**1,386,198 CCF**		**1,454,345 CCF**

Table 8: 95% Confidence interval for Segment 2 Conditional Demand and Total Revenue

	Conditional Demand	***Total Revenue***
Estimated Value	Q= $e^{(2.48-.08MP_{Block2})}$	TR= $MP_{Block2} \times e^{(2.48-.08MP_{Block2})}$
Upper Bound	Q= $e^{(2.48-0.073MP_{Block2})}$	TR= $MP_{Block2} \times$ $e^{(2.48-0.073MP_{Block2})}$
Lower Bound	Q= $e^{(2.48-0.083MP_{Block2})}$	TR= $MP_{Block2} \times e^{(2.48-0.083MP_{Block2})}$

Table 9: 95% Confidence interval for Segment 3 Conditional Demand and Total Revenue

	Conditional Demand	***Total Revenue***
Estimated Value	Q= $e^{(2.27-.036MP_{Block3})}$	TR= $MP_{Block3} \times e^{(2.27-.036MP_{Block3})}$
Upper Bound	Q= $e^{(2.27-.035MP_{Block3})}$	TR= $MP_{Block3} \times e^{(2.27-.035MP_{Block3})}$
Lower Bound	Q= $e^{(2.27-.039MP_{Block3})}$	TR= $MP_{Block3} \times e^{(2.27-.039MP_{Block3})}$

Table 10: 95% Confidence interval for Segment 4 Conditional Demand and Total Revenue

	Conditional Demand	***Total Revenue***

Estimated Value	Q= $e^{(2.26-.012MP_{block4})}$	TR= $MP_{Block4}\times e^{(2.26-.012MP_{block4})}$
Upper Bound	Q= $e^{(2.26-.011MP_{Block4})}$	TR= $MP_{Block3}\times e^{(2.26-.011MP_{Block4})}$
Lower Bound	Q= $e^{(2.26-.015MP_{Block4})}$	TR= $MP_{Block3}\times e^{(2.26-.015MP_{Block4})}$

Table 11: Confidence interval estimates for unconditional segment demand

Demand Equation	$\widehat{\boldsymbol{\beta}_{AP}}$	95% confidence Interval about $\widehat{\boldsymbol{\beta}_{AP}}$
$\mathbf{lnQ_{seg\_1}=2.16-0.08}\boldsymbol{AP}_{\mathbf{seg\_1}}$	-.08	± 0.0184

$\ln Q_{seg\_2}$=3.09-0.11AP_{seg_2}	-.11	± 0.0072
$\ln Q_{seg\_3}$=3.4-.07AP_{seg_3}	-.07	± 0.0046
$\ln Q_{seg\_4}$=3.68-.03AP_{seg_4}	-.03	± 0.0046

Figures Captions List

Figures:

Figure 1: Segment Demand and IBR Schedule FY 2010-2011

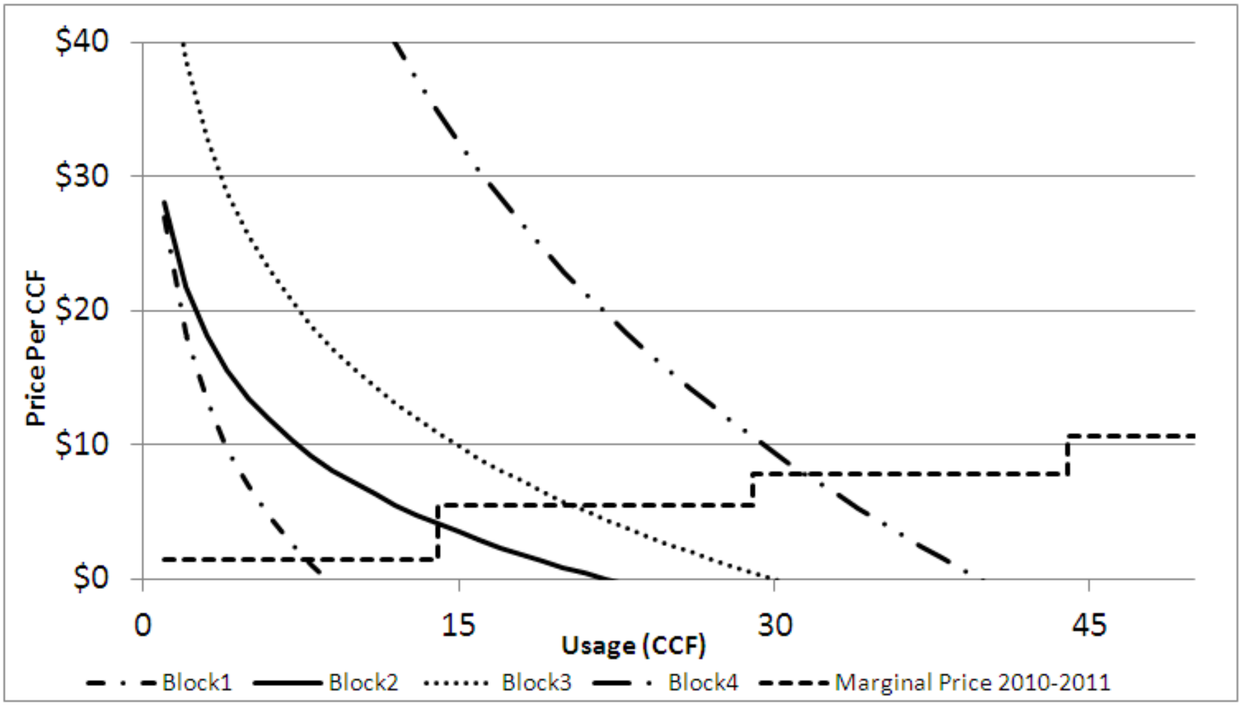
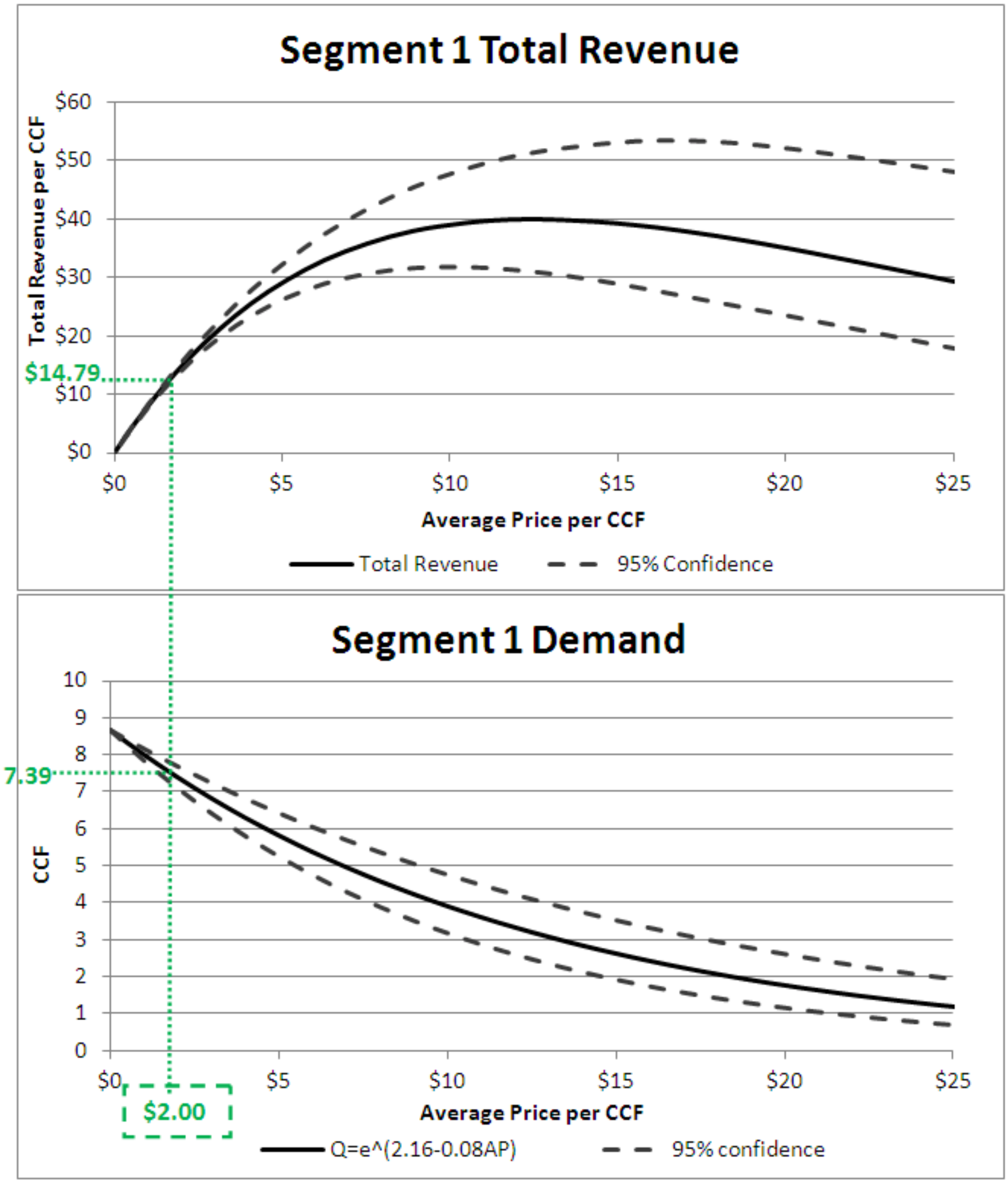


Figure 2: Segment 1 Demand and Total Revenue Curves



(a)

(b)

Figure 3: Segment 2 Demand and Total Revenue Curves

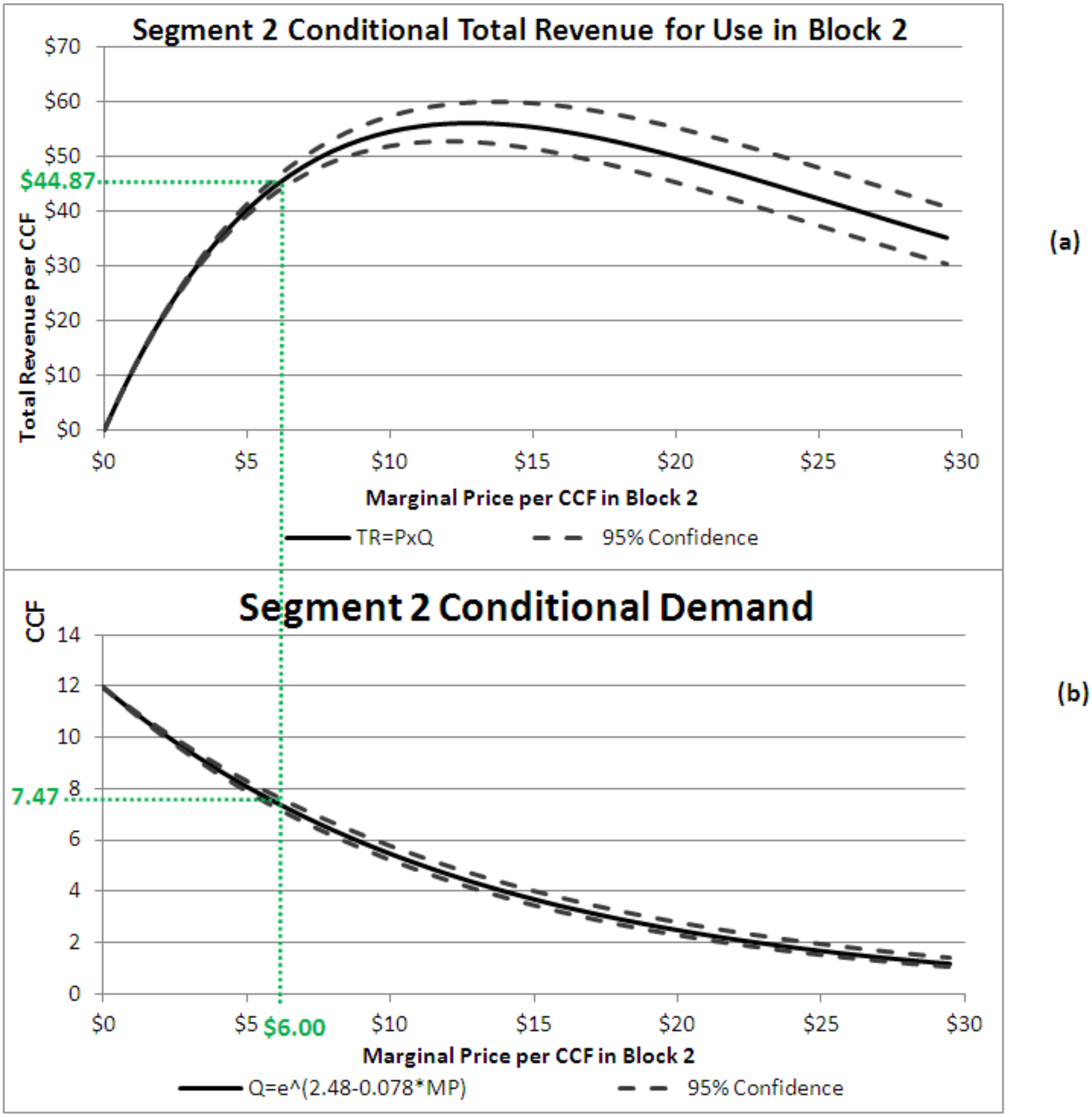


Figure 4: Proposed Increasing Block Rate Schedule

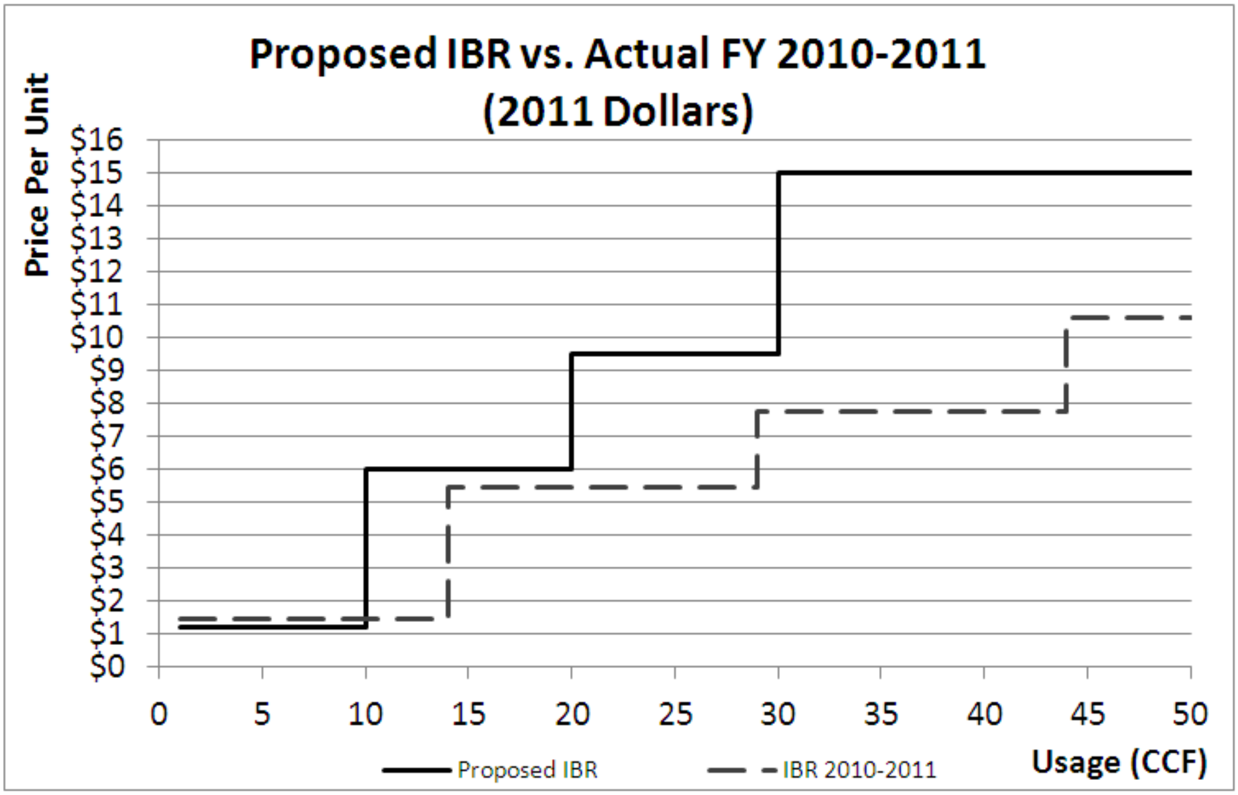


Figure 5: Segment 3 Demand and Total Revenue Curves

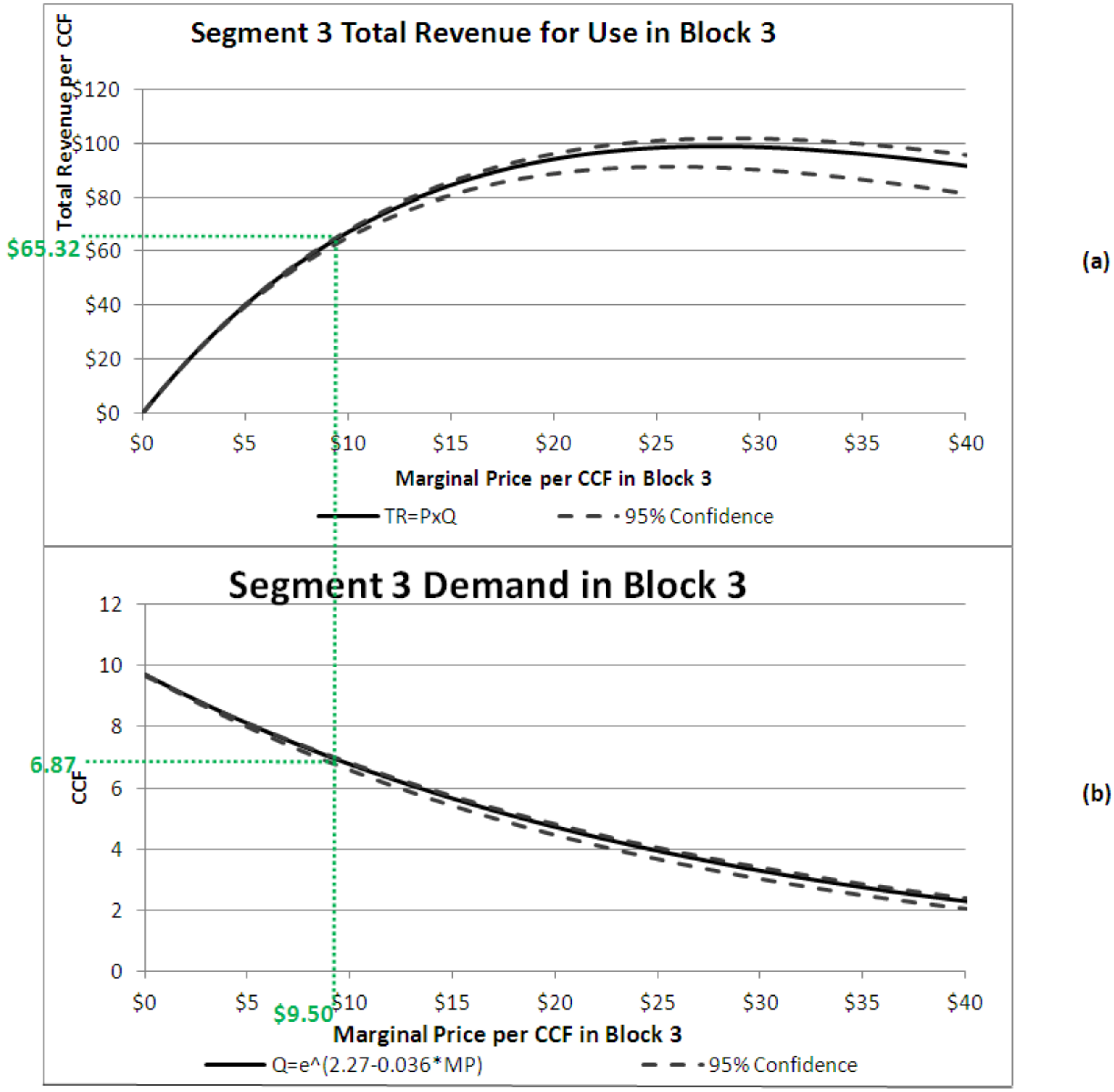


Figure 6: Segment 4 Demand and Total Revenue Curves

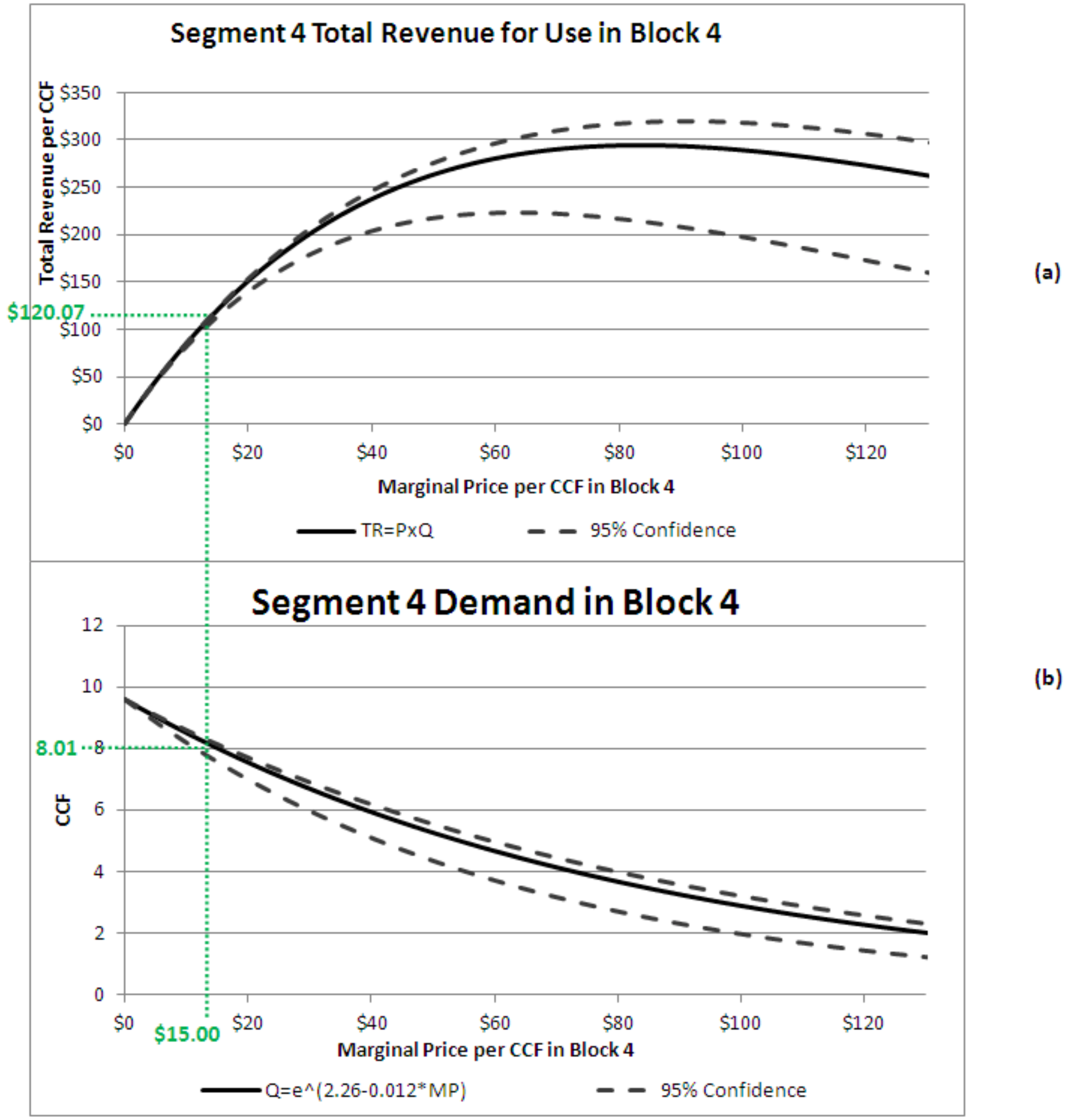


Figure 7: Segment 2 User Demand and Reduction of Consumer Surplus

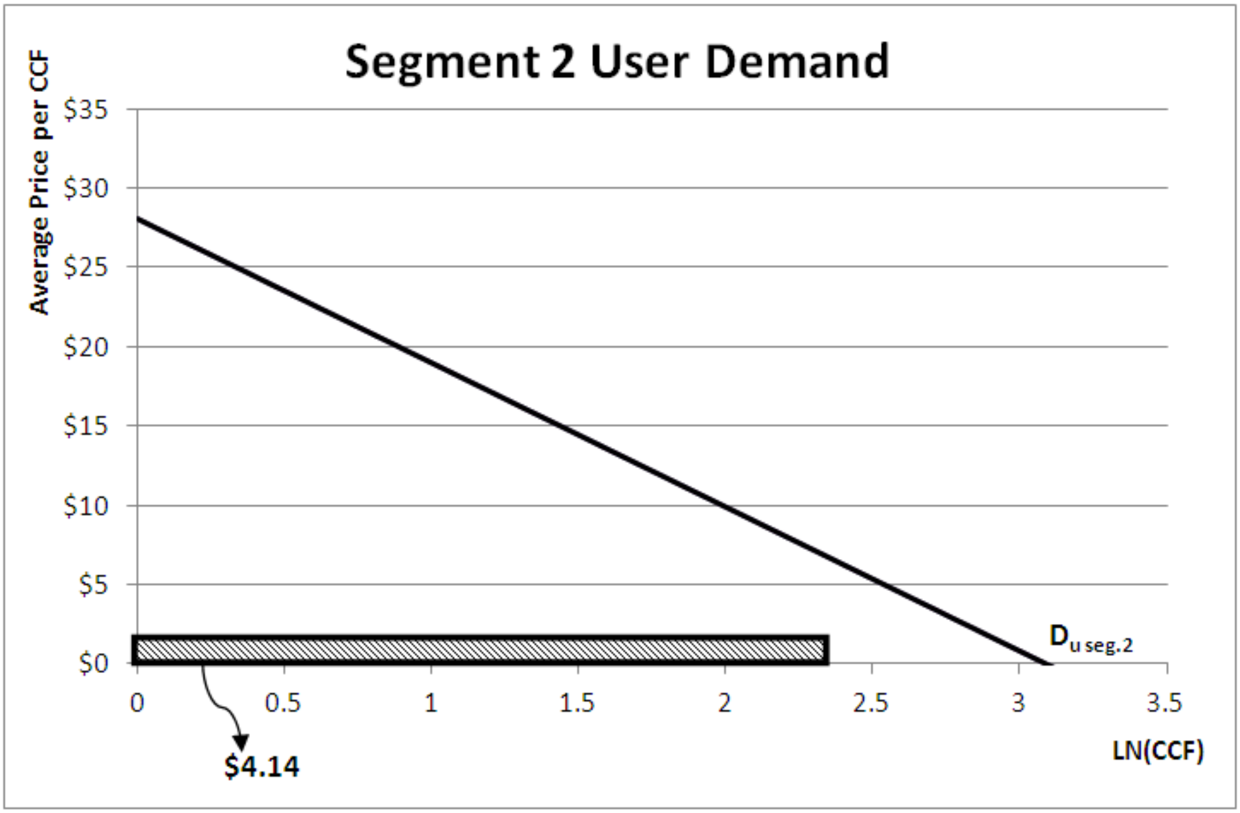


Figure 8: Segment 2 User Demand and Conditional Demand

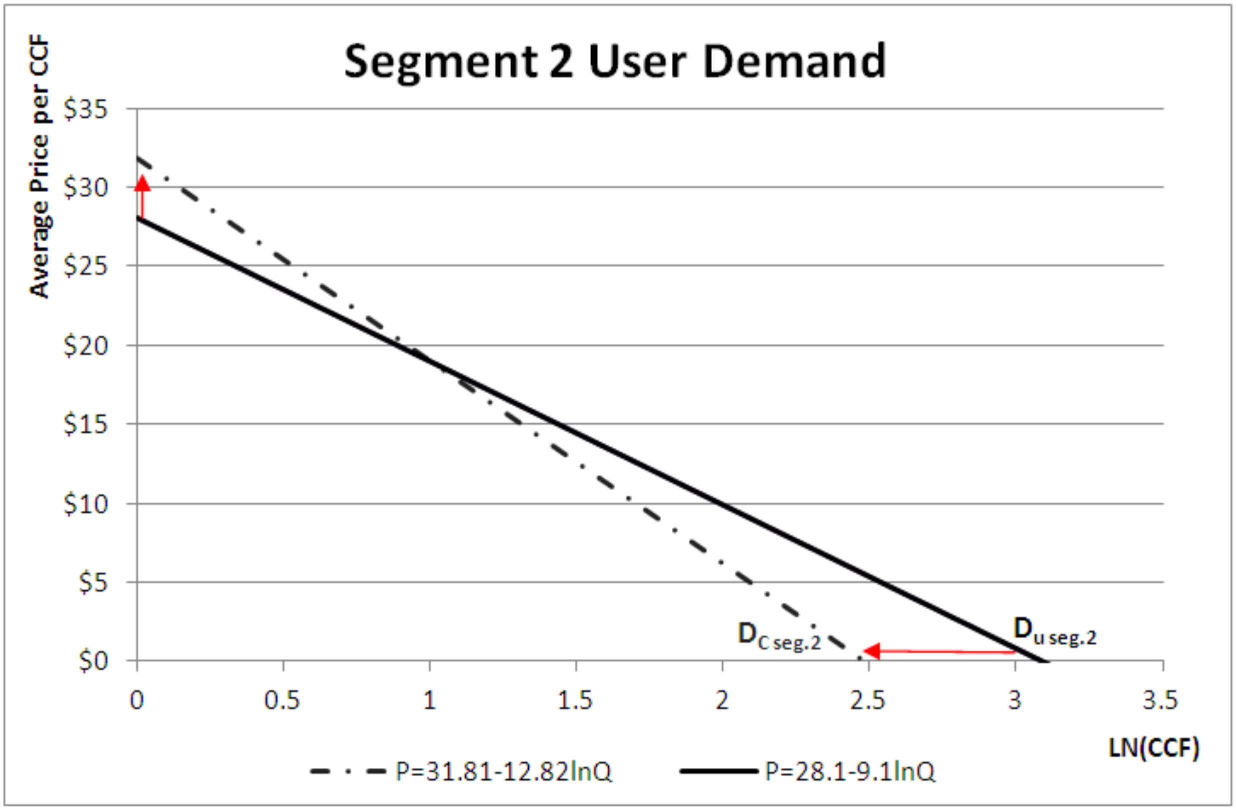


Figure 9: Segment 3 User Demand and Reduction of Consumer Surplus

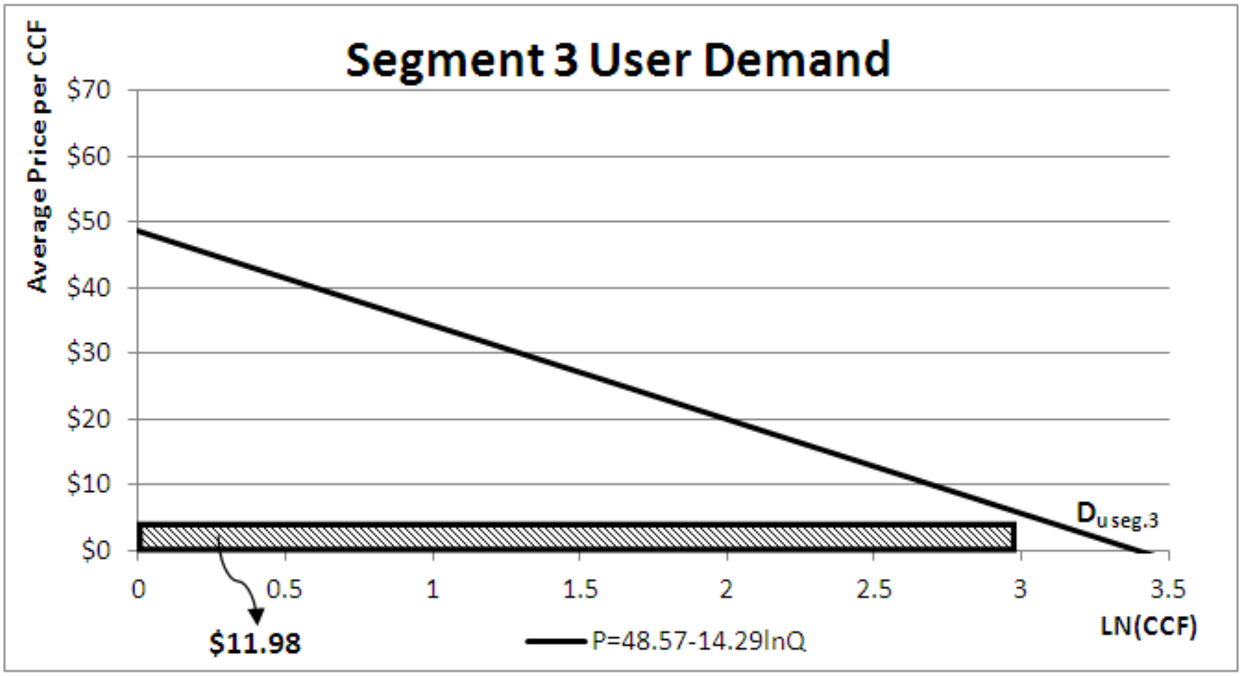


Figure 10: Segment 3 User Demand and Conditional Demand

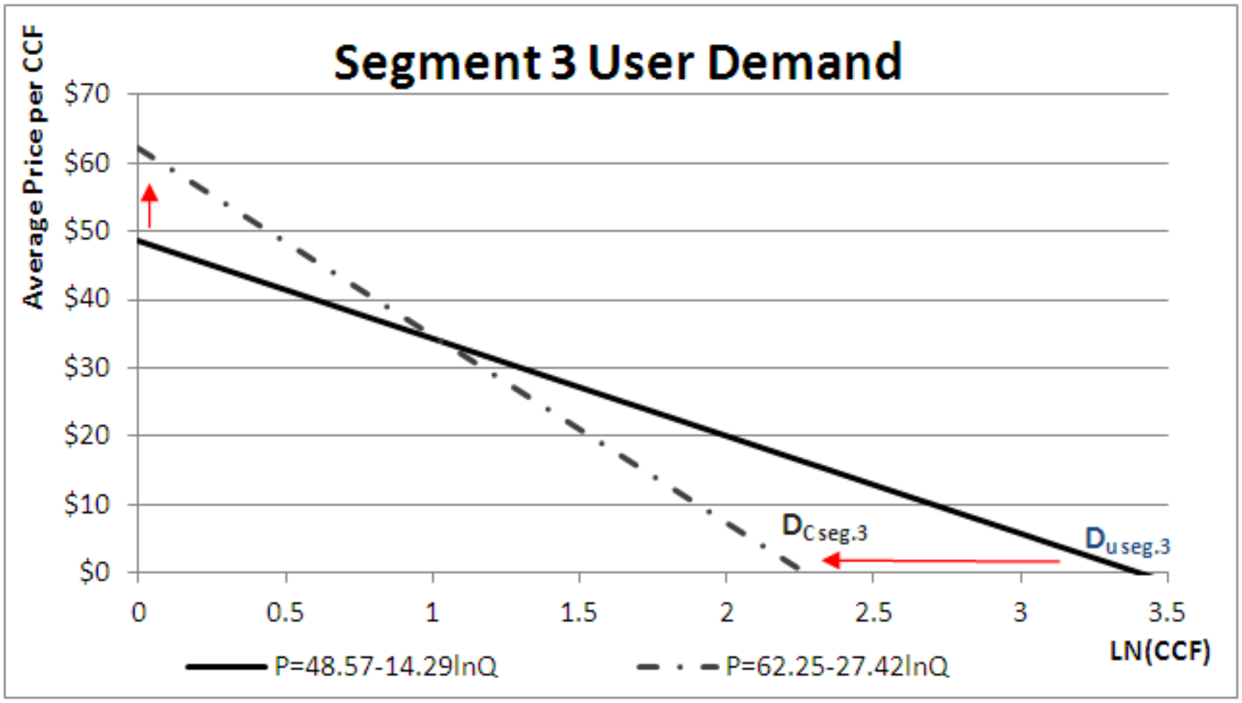


Figure 11: Segment 4 User Demand and Reduction of Consumer Surplus

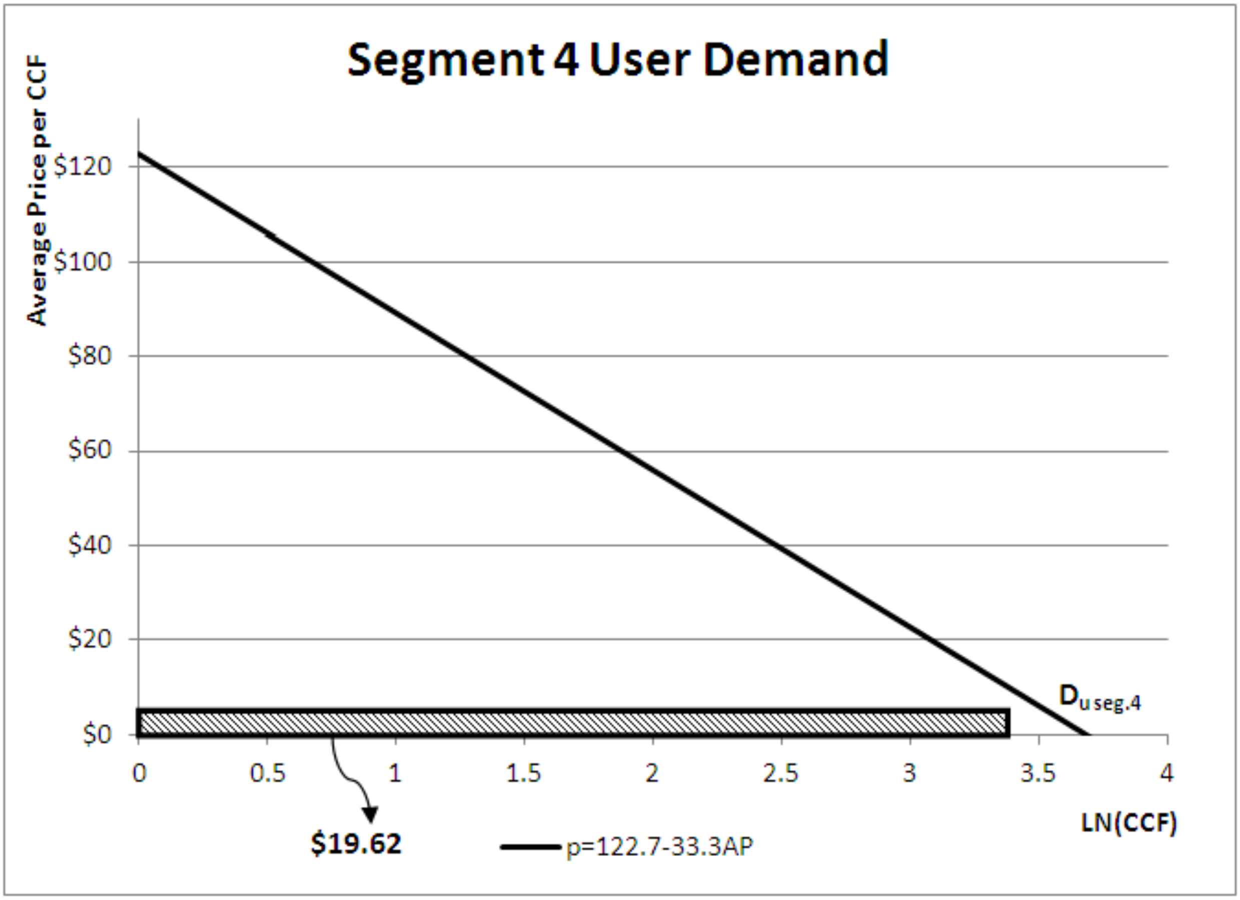


Figure 12: Segment 3 User Demand and Conditional Demand