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Estimating and Verifying Household Potential to Conserve Water

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ESTIMATING AND VERIFYING HOUSEHOLD POTENTIAL TO CONSERVE WATER

by

Francisco J. Suero

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

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UTAH STATE UNIVERSITY
Logan, Utah

2010

ABSTRACT

Estimating and Verifying Household Potential to Conserve Water

by

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Utah State University, 2010

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This thesis identifies impacts of behaviors and technology on residential indoor water use and conservation efforts. We use pre-existing detailed end-use data collected before and after toilets, faucets, showerheads, and clothes washers were retrofitted in 96 owner-occupied, single-family households in Oakland, California; Seattle, Washington; and Tampa, Florida between 2000 and 2003.

Water volume, duration of use, and time of use were recorded and disaggregated by appliance for two weeks before and four weeks after appliances were retrofitted. For each appliance, we compare observed differences in water use before and after retrofits to water savings predicted by analytical engineering, semi-analytical engineering, and econometric regression methods.

Results show that observed and predicted distributions of water savings are skewed with a small number of households showing potential to save more water. Results also show the relative and significant influence on water saved of both technological (flow rates of appliances) and behavioral (length of use, frequency of use) factors. Additionally, the number of residents, and the performance and the frequency of use of the appliance are the key factors that distinguish households that save the most water from households that save less. Study results help improve engineering methods to estimate water savings from retrofits and allow water utilities to better target subcategories of households that have potential to save more water.

(43 pages)

DEDICATION

I dedicate this work to God, for giving me the opportunity of being here. To my family, for their unconditional support throughout my education and formation both at school and at home. To Courtney, for making happiness easier to find. To my friends, for encouraging me to pursue my goals and work hard to achieve them. To the Dominican Government, for providing the funds and support for me to attend Utah State University. To everyone who made possible these two amazing years of my life.

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Francisco J. Suero

CONTENTS

Page

ABSTRACT……ii

DEDICATION iv

ACKNOWLEDGMENTS..v

LIST OF TABLES vii

LIST OF FIGURES viii

CHAPTER

1. INTRODUCTION 1

2. OBJECTIVES OF THE RESEARCH.. 5

3. THE DATA SET... 6

4. ANALYSIS METHODS 10

    4.1 Actual Savings 10
    4.2 Analytical Models... 10
    4.3 Regression Models.. 12
    4.4Semi-Analytical Regression Models 14

5. RESULTS………… 16

    5.1 Toilet Models 16
    5.2 Shower Models 19
    5.3 Clothes Washer Models 21
    5.4 Faucet Models... 23

6. TAILS ANALYSIS 27

7. DISCUSSION.. 29

8. CONCLUSIONS AND RECOMMENDATIONS.. 32

REFERENCES…. 34

LIST OF TABLES

Table Page

1 Energy Policy act 7

2 Summary of average savings by location and appliance. 8

3 Summary of toilet technological regressions 17

4 K-S test results for toilet models. 19

5 Summary of showerhead technological regressions. 20

6 K-S test results for shower models. 21

7 Summary of clothes washer technological regressions. 22

8 K-S test results for clotheswasher models. 23

9 Summary of faucet technological regressions. 24

10 K-S test results for faucet models. 26

11 Comparing characteristics of households 28

LIST OF FIGURES

Figure Page

1 Distribution among households of water saved 9

2 Cumulative distribution of water saved by retrofitting toilets 18

3 Cumulative distribution of water saved by retrofitting showerheads.................... 20

4 Cumulative distribution of water saved by retrofitting clothes washers 22

5 Cumulative distribution of water saved by retrofitting faucets.............................. 25

6 Observed and analytical estimates of water saved.. 30

7 Observed and semi-log regressions estimates of water saved............................... 30

CHAPTER 1

INTRODUCTION

Urbanization and growing populations are placing increased demands on scarce, limited, municipal water supplies. Compared to expensive supply-side options to expand municipal or regional water infrastructure, residential water conservation can cost effectively help demands match available supplies. Conservation can include technological changes, such as replacing old toilets, faucets, showerheads, dishwashers, and laundry machines with newer and more efficient appliances mandated by the 1992 federal U.S. Energy Policy Act (EPA). Newer appliances use less water per flush, per minute, or per wash cycle, can reduce or fix associated leaks, and contribute to significant water savings, such as a 31% reduction in demand (Wallander, 2009). However, to include water conservation in water supply/demand planning, it is important to correctly forecast both (i) water demands and (ii) the volume of water potentially saved by conservation actions.

Planners and water managers have long tried to forecast water demand and estimate reductions in water demand and water savings from conservation programs and measures (Berk et al., 1993; Buchberger and Wells, 1996; Kenney et al., 2008; Michelsen, McGuckin, and Stumpf., 1999; Renwick and Archibald, 1998; Walski et al., 1985). To determine the effectiveness of water conservation measures, the effectiveness of each measure must be determined (Walski et al., 1985). For example, low flow showerheads and toilet dams were distributed among Hamilton Township residents in 1978; subsequently customers were surveyed to identify the number of devices actually installed, and coefficients obtained from this data were used in an algorithm to predict water savings (Walski et al., 1985). Data loggers have been installed on the supply line for single family residences, recording the total instantaneous water demand of the household (Buchberger and Wells, 1996). Models to estimate household-level water demands have been developed as a function of price, weather, house and household characteristics, as well as other policy restrictions and interventions during the study periods (Kenney et al., 2008). Water conservation program planners can also probabilistically describe the volume of water saved from conservation actions by delineating ranges of values for costumer demographic, behavioral, and technological parameters influencing water savings and describing how those parameters combine (Rosenberg, 2007). To make a precise estimate of water savings, it is necessary to analyze and model the performance of the plumbing fixtures and the use of these fixtures (Wallander, 2009).

Having more efficient appliances does not provide a direct way to estimate savings because human behaviors also play an important role—the duration and frequency of appliance use. Additionally, when people know they are using a water-conserving appliance, they may use the appliance longer or more frequently. This increased use may swamp expected water savings (Campbell, Johnson, and Hunt, 2004).

Despite much water conservation work and study, demand forecasting and conservation estimation methods can be improved in several ways. First, water saving estimates need to be empirically verified. More carefully gathering and storing observations of water use and pairing them to estimates can help with empirical verification (Walski et al., 1985). Second, household heterogeneity needs to be more explicitly considered (Whitcomb, 1990; Rosenberg, 2007). Studies typically include a wide variety of explanatory variables (such as income, household size, lot size, age of house, etc.) to characterize household heterogeneity, but use only one aggregate dependent variable--monthly billed water use (Kenney et al., 2008). Using more-detailed end use data for each water appliance can add more specificity. Third, technological and behavioral factors influencing water savings can be better described and disentangled. For example, the duration and frequency each resident in a household uses an appliance may differ. At the same time, the flow, flush, or use rate of an existing appliance can depend on numerous factors including when the appliance was manufactures and whether it has been maintained. Similarly, the flow, flush, or use rate of a retrofitted appliance set by the manufacture may differ from the installed or actual rate. Thus, water use and savings depend on both technological and behavioral factors acting together.

To improve methods to forecast demands and estimate the water saved when a household implements a water conservation action, this study presents analytical, semi-analytical, and regression models to estimate the water saved when retrofitting water appliances. Model variables include pre-existing and retrofitted flush and flow rates of water appliances, such as toilets, showerheads, faucets and clothes washers. Also, the models use behavioral variables such as the duration and frequency of appliance use. In this way, the models separate technological and behavioral factors affecting water use and savings. The study also identifies households with the potential to conserve the most water. Models are built from and results verified against detailed water end-use data collected at 10-second intervals and disaggregated by appliance for 96 households in Oakland, CA; Seattle, WA; and Tampa, FL between 2000 to 2003 (USEPA, 2004). The dataset includes several weeks before and after each household was retrofitted with water efficient toilets, faucets, showers, dishwashers, and clothes washers. Herein, the analysis methods used for the analytical, semi analytical, and regression models are presented, as well as the methodology used to calculate the actual water savings. Models results are shown by appliance and we highlight ways water utilities can target retrofits to households with potential to save the most water.

CHAPTER 2

OBJECTIVES OF THE RESEARCH

This study aims to improve engineering methods to estimate water savings and aid water utilities to better target subcategories of households with larger potential to save water. The objectives can be summarized as follows:

1. Develop models to estimate household water conservation potential.
2. Identify variables that most influence the volume of water conserved.
3. Differentiate household potential to conserve water based on household technological and behavioral characteristics.
4. Identify households with the most potential to conserve water.

CHAPTER 3

THE DATA SET

This work uses end-use data previously collected by Aquacraft, Inc in a project funded by the U.S. Environmental Protection Agency (USEPA, 2004). Aquacraft collected water use data from 96 single-family houses in Seattle, WA, East Bay Municipal Utility District (EBMUD), and Tampa, FL., between 2000 and 2003 for two weeks before and four weeks after each household was retrofitted with water efficient appliances. Aquacraft recorded water use by placing data loggers on each participating household's water meter. The data logger recorded water flow through the meter at 10 seconds intervals and flow signals were post processed to determine the duration, water volume, and frequency of household leaks, outdoor, and indoor water uses (including toilets, showers, clothes washers, faucets) (USEPA, 2004).

The houses selected for the study used more than 60 gallons per capita per day and were representative of households in the three cities. Participating homes averaged 46 years in age. Old homes are less likely to have water-conserving appliances. Aquacraft, Inc. also collected additional socio-demographic data on each participating household, including persons per household, children per household, number of bedrooms, number of bathrooms, floor area, and price paid for water.

Water use data collected for the two weeks before the retrofit constituted the base line water use for each household. Next, water appliances were retrofitted with more efficient ones, i.e., existing toilets were replaced with low flush volume toilets. The 1992 Energy Policy Act (EPA) instituted federal restrictions on the maximum flow rates for all plumbing fixtures sold in the U.S. as a way to reduce water demand. Table 1 shows the restrictions applied by the EPA to the appliances used in this study.

One month after the retrofit, water use was again recorded for two weeks. Finally, six months after the retrofit, water use was logged for two more weeks to identify behavioral changes and the persistence of water savings from the retrofits.

In general, households reduced the water use after they were retrofitted with the new appliances (Table 2). Tampa households had the highest use pre retrofit and were retrofitted with the most efficient appliances, which explain why those houses had the biggest water savings.

Table 1. Energy Policy Act - mandated performance standards for water appliances

Appliance	**Maximum Water Use**
Gravity Tank Type Toilets (gallons per flush)	1.6
Faucets (gallons per minute)	2.5
Showerheads (gallons per minute)	2.5
Dishwasher and Clothes washer	None specified

Table 2. Summary of average savings by location and appliance

Location/ Appliance	Water Use Pre-Retrofit [gal/hh/year]	Water Use Post-Retrofit [gal/hh/year]	Water Saved [gal/hh/year]
EBMUD	65,266	44,195	21,071
- Toilet	16,930	8,000	8,929
- Shower	10,598	9,394	1,204
- Clotheswasher	28,724	18,078	10,646
- Faucet	9,014	8,723	291
Seattle	57,632	37,315	20,317
- Toilet	16,007	6,837	9,170
- Shower	7,483	7,331	152
- Clotheswasher	26,912	16,563	10,350
- Faucet	7,230	6,585	645
Tampa	82,760	30,822	51,938
- Toilet	17,780	7,460	10,320
- Shower	11,450	9,417	2,032
- Clotheswasher	26,567	7,460	19,108
- Faucet	26,963	6,485	20,478

But averages can hide distributions among users. In the USEPA (2004) data, six homes did not save any water after retrofits, while other households saved more than 200,000 gallons per year (Figure 1). Overall, 93% of the households saved water, showing that retrofits can be effective. The distribution also shows that utility companies can have successful conservation programs with reduced effort if they can target programs to households on the right tail with the most potential to conserve water.

Herein, we use the end-use data collected in the USEPA (2004) study to develop models to estimate water savings. Estimated water savings are verified against observed savings and also we show how to identify households with the potential to conserve the most water.

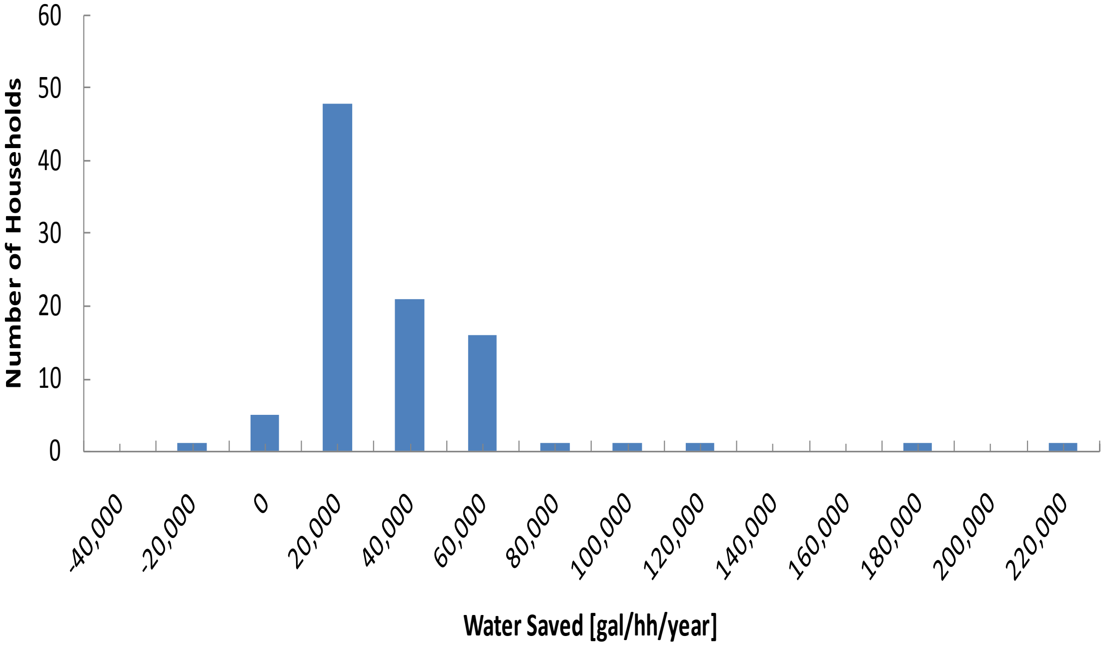


Figure 1. Distribution among households of water saved by retrofitting toilets, showers, faucets, and clothes washers.

CHAPTER 4

ANALYSIS METHODS

Analytical and regression methods are used to estimate water saved and estimates are compared to the actual water saved by households participating in the USEPA study. The methods used in this research have as an objective to predict the savings observed. Below, the methods to calculate actual savings and develop analytical, regression, and semi-analytical models are described.

4.1 Actual Savings

First, actual water savings were calculated by subtracting the volume of water used by each appliance during the pre-retrofit period from the volume used during the post-retrofit period. Since the pre-and post-retrofit periods were different lengths of time, we used average daily use values and then extrapolated average daily savings to a per household per year basis.

4.2 Analytical Models

Second, an analytical model was developed for each appliance retrofitted. The analytical model calculates water savings from first principles and multiplies the expected change in water volume per use associated with the appliance retrofit by the frequency of appliance use and by the number of people in the household. The expected change in water volume per use is calculated by subtracting the post-retrofit flow rate (gallons per use) from the pre-retrofit flow rate. A separate analytical model was developed for each appliance. For example, the analytical model to estimate the water saved by retrofitting a showerhead was:

$$W_{analytical} = a[(b)-(d)]*c*365 \tag{1}$$

where:

$W_{analytical}$ = water saved by the appliance (in this case by the showerhead) as estimated using the analytical model [gal/household/year].

a= Persons per Household. Permanent residents in the homes at the time the study was done [persons/hh]

b= Average flow rate of appliance pre-retrofit [gal/min]

c= Average shower time per person per day [min/person/day]

d= Average flow rate of appliance post-retrofit. [gal/min]

Average flow rates were calculated by dividing the total water use by the shower during the pre- or post-retrofit period by the total time it was used during that same period. The average shower time is the total use time over the pre and post retrofits periods divided by the number of residents in the house and the number of days of the pre- or post-retrofit period. The pre- and post-retrofit use frequencies were different for toilets and clothes washers, hence, the term “c” couldn’t be taken out of the parenthesis for those appliances; in those models, the use terms were combined with the flow rates as part of the difference term. Since some appliances weren’t used every day during the study period, the use per day is calculated only taking into account days that the appliance was actually used.

4.3 Regression Models

Third, we also used several regressions methods to explain water savings as a function of different independent variables. Regression models use the same variables as the analytical models, but include coefficients to improve the fit between actual and estimated savings. These independent variables include the number of persons per household, pre- and post-retrofit volumes per use, and the frequency of use of each appliance. The regression models can help disentangle technological (volume per use), behavioral (frequency of use), and economic factors (water price) and their relative influences on water use and water saved by retrofits.

The water saved by retrofitting each household water appliances was estimated from variables describing the technological function of the water use appliance such as the flush rate of toilets, flow rates of shower and faucets, and gallons per load for laundry machines. Different regressions were tested: linear, log-log, semi-log, and semi-log with location to test different model structures and simulate the water savings distribution.

For example, a semi-log model is shown in Equation 2.

$$W_{semi\log} = a_1 \ln x_1 + a_1 \ln x_2 + a_3 \ln x_3 + a_4 \ln x_4 + b + e \qquad (2)$$

where:

$W_{semilog}$ = actual water saved by the appliance (in this case by the toilet) [gal/household/year]

a_n = Regression coefficients

x_1= Average pre-retrofit flow rate [gal/min]

x_2= Average post-retrofit flow rate [gal/min]

x_3= Persons per household [# of permanent residents]

x_4= Average use frequency [min/person/day]

b = Intercept [gal/hh/year]

e= Random effects not explained by model variables [gal/hh/year]

For the semi-log models developed for shower and other water appliances, the natural log of the variables was calculated, and then the regression coefficients were identified using linear least-squares regression.

The econometric regressions use variables related to socio-economic characteristics of the households, which were taken from the surveys performed by Aquacraft, Inc. With the econometric regression, the objective is to identify relationships between water use and water saved and variables such as the price paid per unit of water used and/or the size of the house. These regressions also allow us to identify and distinguishing high savers from low savers.

4.4 Semi-Analytical Regression Models

Semi-analytical (log-log) models were developed for each appliance (Equation 3). These log-log regressions estimate savings using both technological and behavioral variables, a hybrid between analytical and regression models. They take the log of the analytical model (Eq. 1), then add coefficients to improve the fit (Equation 3).

$$\ln(W_{semi\log}) = a_1 \ln(x_1 - x_2) + a_3 \ln x_3 + a_4 \ln x_4 + b + e \tag{3}$$

where:

Ln($W_{semilog)}$ = Natural log of actual water saved by the appliance (in this case by the toilet) [gal/household/year]

a_n =Regression coefficients

x_1= Average pre-retrofit flow rate [gal/min]

x_2= Average post-retrofit flush volume [gal/min]

x_3=Persons per household [# of permanent residents]

x_4= Average use [min/person/day]

b = Intercept [gal/hh/year]

e= Random effects not explained by model variables [gal/hh/year]

The semi-analytical model has the limitation of not being able to estimate negative savings (houses that did not save water), therefore households that did not save water were dropped from the analysis. Also, the use before and after retrofits was significantly different for toilets and clotheswashers, so both pre and post retrofits frequency of use variables were included in the semi-analytical models for these appliances.

CHAPTER 5

RESULTS

Herein, results from the analytical, semi-analytical, and regression models are presented by appliance. For each regression model we developed, we report regression coefficient values, t-statistics, and the r^2 showing the fraction of variation in the dependent variable (water saved) that is explained by the model variables. A Kolmogorov-Smirnov test was also used to compare resulting distributions of water saved by the analytical, semi-analytical, and regression models to the actual water saved. The Kolmogorov-Smirnov test (KS-test) tries to determine if the distribution of two datasets differ significantly, and makes no assumption about the distribution shapes or the sample size (Chakravarti, Laha, and Roy, 1967). The K-S test gives a D value, D being the maximum difference between the two cumulative density functions tested. The null hypothesis of no difference between distributions should be rejected if P is small (<0.05).

5.1 Toilet Models

Analytical and regression models were tried, with the analytical, semi-log and the semi-log with location models having the best fit, and therefore most effectively explaining water savings as a function of the independent variables use. Table 3 shows a summary of the regression models calculated for the toilet; with water savings given in gallons per household per year [gal/hh/year]. In these models (as in Equation 2 and 3), 'a' is the coefficient of each variable, 'b' is the intercept, and 'ê' is the effect not explained by the variables.

In all models, both the technological and behavioral variables (i.e., flush volumes and frequencies of use) are significant and have the expected signs. The semi-log and semi-log with location models (models 1 and 2), show the best fit with the highest r^2. In these models, both technological and behavioral variables have large influences. Since both regressions have the same fit, the only difference between them is adding the independent variable "location" to the second model. Results show that the location of the household is not a significant variable and does not alter household's water savings by toilet use and retrofit.

Table 3. Summary of technological regression models for water saved when retrofitting toilets

Model	Variable	Elasticity	t-stat
1. Semi-Log, $W_{semi\text{-}log} = a_1 \ln x_1 + a_2 \ln x_2 + \ldots + a_i \ln x_i + b + \hat{e}$ (N=96; r^2=0.88)			
	Average Pre-Retrofit Flush Volume [gal/flush]	2.00	21.25**
	Average Post-Retrofit Flush Volume [gal/flush]	-0.87	-4.96**
	Persons Per Household [# of permanent residents]	0.77	8.18**
	Average Flushes-Pre-Retrofit [#/person/day]	1.85	16.67**
	Average Flushes-Post-Retrofit [#/person/day]	-0.89	-7.68**
2. Semi-Log with Location, $W_{semi\text{-}log\ location} = a_1 \ln x_1 + a_2 \ln x_2 + \ldots + a_i \ln x_i + b + \hat{e}$ (N=96; r^2=0.88)			
	Location	0.10	1.11
	Average Pre-Retrofit Flush Volume [gal/flush]	2.00	21.27**
	Average Post-Retrofit Flush Volume [gal/flush]	-0.92	-5.08**
	Persons Per Household [# of permanent residents]	0.76	7.97**
	Average Flushes-Pre-Retrofit [#/person/day]	1.85	16.67**
	Average Flushes-Post-Retrofit [#/person/day]	-0.89	-7.67**
3.Semi-Analytical, $\ln(W_{semi\text{-}analytical}) = a_1 \ln(x_1 x_4 - x_2 x_5) + a_i \ln x_i + b + \hat{e}$ (N=85; r^2=064)			
	Average Change in Water Use [gal/person/day]	1.78	11.41**
	Persons Per Household [# of permanent residents]	1.01	6.08**

**Significant at the 95% level.

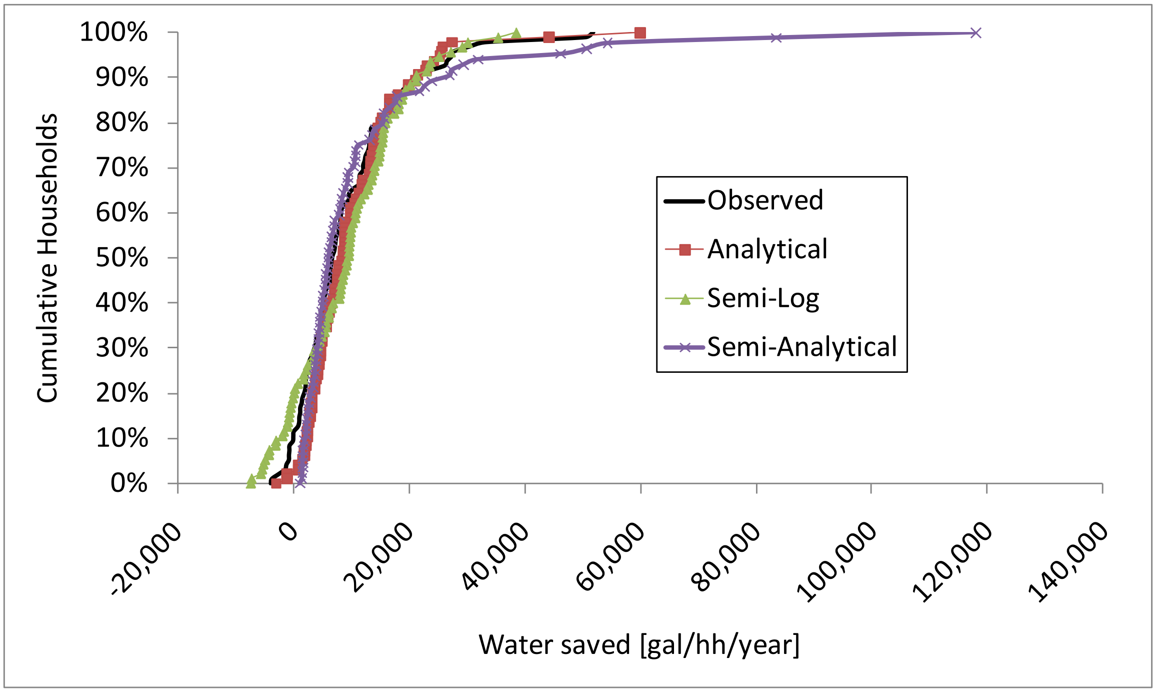


Figure 2. Cumulative distribution among households of water saved by retrofitting toilets.

Figure 2 presents the cumulative distributions of observed and modeled water savings among households. It shows the analytical, semi-log, and semi-analytical models predict distributions of savings among households similar to observed savings. The observations are confirmed by K-S tests (P ≥ 0.05 for all models; Table 4). The analytical and semi-log models have the smallest D values and are likely the most similar to the observed distributions of savings. The distributions of savings predicted by semi-analytical model over estimates savings, which increases the difference (Figure 2).

The regression and K-S test results show that the analytical and semi-log models can be effectively used to estimate residential savings when retrofitting toilets.

Table 4. K-S test results for toilet models

Model	**K-S Stat (D)**	**Significance (P)**
Analytical	0.167	0.13
Semi -Log	0.167	0.13
Semi-Analytical	0.186	0.08

5.2 Shower Models

Table 5 shows the results for the regression models developed to estimate water saved by retrofitting showerheads. In this model the average shower length per person per day was used. Since the difference between showering time per person per day before and after the retrofits was not significantly greater than zero (t-stat= -0.59, P= 0.55), this model used one average shower length per person. The technological variables, the appliance flow rate, and the number of permanent residents are significant.

The semi-log model provides a fit of r^2= 0.27. The elasticity values show what is expected: post retrofit showerhead flow rate variable reduces water use, and increases savings. Technological variables are significant at the 95% level for both regression models, while the behavioral component is only significant at the 95% level in the semi-analytical model. According to the elasticity values shown on Table 5, technological factors have larger effect on savings than behavioral factors. For the semi-log model, the shower length variable is significant at the 52% level.

Figure 3 shows the distributions of water saved among customers and reveals that distributions for the semi-log and semi-analytical models are shifted. The analytical and semi-log models are not able to match the tail (high savers) of the observed savings, while the semi-analytical model does a better job estimating high savings.

Table 5. Summary of technological regression model for water saved when retrofitting showerheads

Model	**Variable**	**Elasticity**	**t-stat**
1. Semi-Log, $W_{semi\text{-}log} = a_1 \ln x_1 + a_2 \ln x_2 + \ldots + a_i \ln x_i + b + \hat{e}$ (N=94; r^2=0.27)			
	Average Pre-Retrofit Flow Rate [gal/min]	4.17	4.47**
	Average Post-Retrofit Flow Rate [gal/min]	-3.15	-2.05**
	Persons Per Household [# of permanent residents]	2.013	3.17**
	Average Shower Length [minutes/person/day]	0.31	0.70
2.Semi-Analytical, $\ln(W_{semi\text{-}analytical}) = a_1 \ln(x_1 - x_2) + \ldots + a_i \ln x_i + b + \hat{e}$ (N=58; r^2=0.36)			
	Average Change in Flow Rate [gal/min]	1.88	4.19**
	Persons Per Household [# of permanent residents]	0.82	3.13**
	Average Shower Length [minutes/person/day]	0.48	2.56**

** Significant at the 95% level.

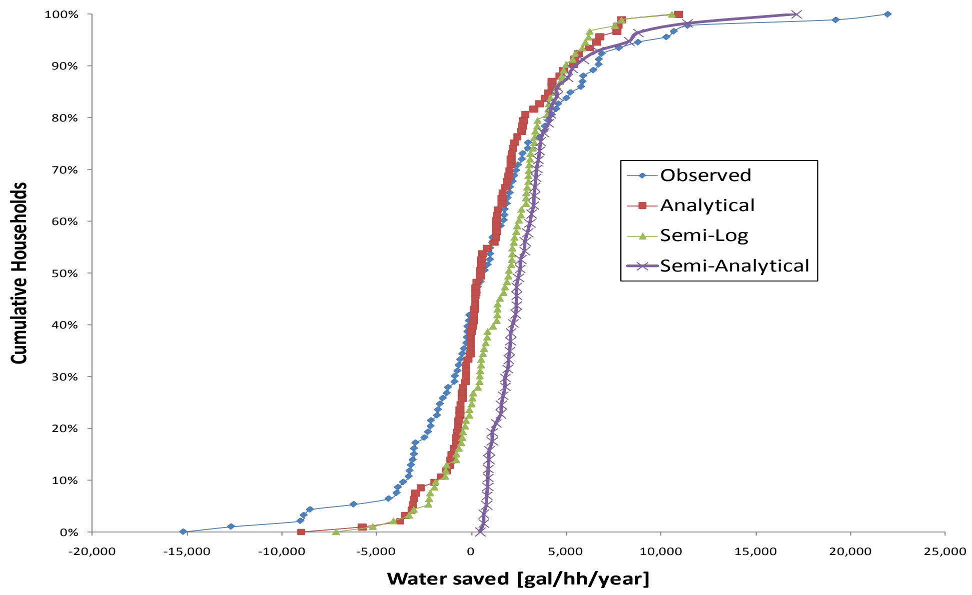


Figure 3. Cumulative distribution among households of water saved by retrofitting showerheads.

Table 6. K-S test results for shower models

Model	**K-S Stat (D)**	**Significance (P)**
Analytical	0.128	0.403
Semi -Log	0.160	0.166
Semi-Analytical	0.472	0.003

When the K-S test was applied to the semi-log model a D value of 16% was obtained, but only significant at the 16% level, and results of the K-S test gave the analytical model a D value of 12% significant at the 40.3% level (Table 6). These results show that the distributions of savings estimated by the analytical and semi-log models are statistically similar to the observed distribution of savings.

5.3 Clothes Washer Models

Table 7 shows regression results for the semi-log and semi-analytical models. For both models, technological and behavioral variables are significant at the 95% level.

In both models of water saved by retrofitting laundry machines, all the variables have the expected signs. The variables with the largest coefficient values are the Average Pre-Retrofit Load Volume, and the Loads Pre-Retrofit [#/person/day]. Again, both technological and behavioral factors affect water savings. Figure 4 shows the distributions for the models and for the observed water savings.

Table 7. Summary of clothes washer technological regressions

Model	Variable	Elasticity	t-stat
1. Semi-Log, $W_{semi\text{-}log} = a_1 \ln x_1 + a_2 \ln x_2 + \ldots + a_i \ln x_i + b + \hat{e}$ (N=95; r^2=0.91)			
	Average Pre-Retrofit Load Volume [gal/load]	2.41	23.92**
	Average Post-Retrofit Flush Volume [gal/load]	-1.83	-10.44**
	Persons Per Household	1.00	7.84**
	Loads- Pre-Retrofit [#/person/day]	2.81	23.85**
	Loads-Post-Retrofit [#/person/day]	-1.82	-13.12**
2.Semi-Analytical, $\ln(W_{semi\text{-}analytical}) = a_1 \ln(x_1 x_4 - x_2 x_5) + a_i \ln x_i + b + \hat{e}$ (N=85; r^2=0.79)			
	Average Change in Water Use [gal/person/day]	1.32	13.93**
	Persons Per Household	0.84	4.81**

** Significant at the 95% level.

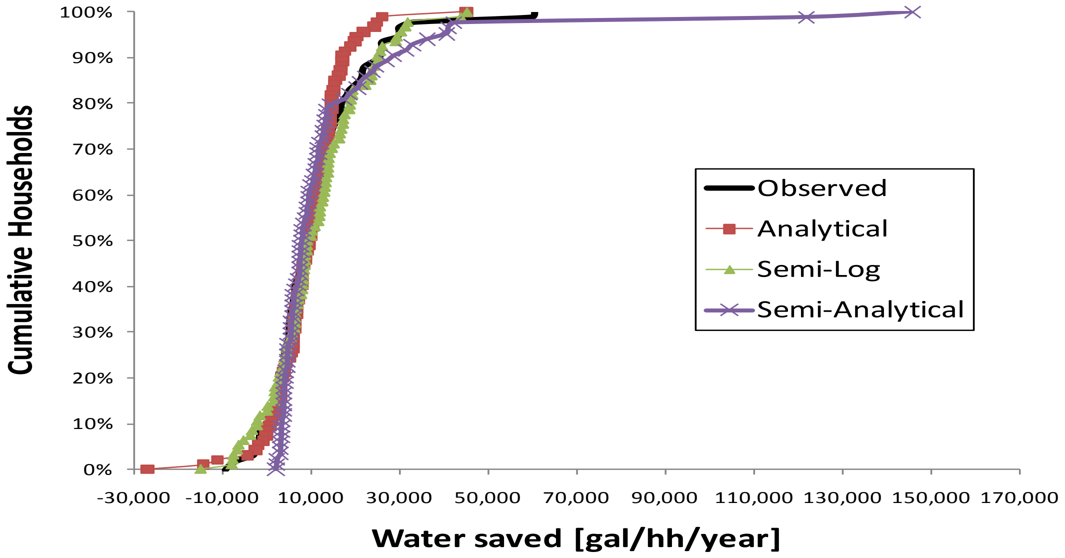


Figure 4. Cumulative distribution among households of water saved by retrofitting clothes washers.

Table 8. K-S test results for clotheswasher models

Model	**K-S Stat (D)**	**Significance (P)**
Analytical	0.105	0.644
Semi-Log	0.084	0.875
Semi-Analytical	0.190	0.07

A K-S test was performed to quantify the significance of fit (Table 8). Results for each model, P >0.05 indicating the modeled distributions of savings are likely similar to the observed savings. The semi-log model distribution is likely the most similar.

Regression and K-S test results show that the analytical and semi-log models fit very well, while the semi-analytical model overestimates savings. Estimating water savings by clothes washers can be done in precise way using analytical and semi-log models, and provides an efficient way to estimate water savings by households based on technological and behavioral characteristics.

5.4 Faucet Models

The analytical model of faucet savings was similar to the one used for the analytical shower model. The faucet model also used average use time, since there wasn’t a significant difference between pre and post retrofit use time.

The semi-log and semi-analytical regressions models have as independent variables the average flow rates pre- and post-retrofits, the number of residents, and the average length of use per person per day (Table 9).

Table 9. Summary of faucet technological regressions

Model	**Variable**	**Elasticity**	**t-stat**
1. Semi-Log, $W_{semi\text{-}log} = a_1 \ln x_1 + a_2 \ln x_2 + \ldots + a_i \ln x_i + b + \hat{e}$ (N=96; r^2=0.70)			
	Average Pre-Retrofit Flow Rate [gal/min]	3.98	8.40**
	Average Post-Retrofit Flow Rate [gal/min]	-3.08	-7.40**
	Persons Per Household [# of permanent residents]	1.62	6.23**
	Average Use [minutes/person/day]	1.84	8.87**
2.Semi-Analytical, $\ln(W_{semi\text{-}analytical}) = a_1 \ln(x_1 - x_2) + \ldots + a_i \ln x_i + b + \hat{e}$ (N=83; r^2=0.73)			
	Average Change in Flow Rate [gal/min]	3.14	9.08**
	Persons Per Household [# of permanent residents]	0.76	4.56**
	Average Use [minutes/person/day]	0.99	7.43**

** Significant at the 95% level.

Semi-log model variables can explain 70% of the variations in water savings. Coefficients associated with each variable all have the expected sign and are significant. The average pre and post retrofit flow rate have the largest coefficient values and most influence faucet water savings. The semi-analytical model also has a similar r^2, although this model only estimates positive savings due to the log-log formulation. These results suggest that technological and behavioral factors influence water savings, but that technological factors are more important in the case of faucet retrofits.

As long as the behavioral components remain constant, savings depend mostly on the performance of the appliances, in this case, faucets. The frequency of use of faucets can be altered by the use of the appliance by non-residents, since visitors will mostly use faucets and toilets, instead of clotheswashers and showers.

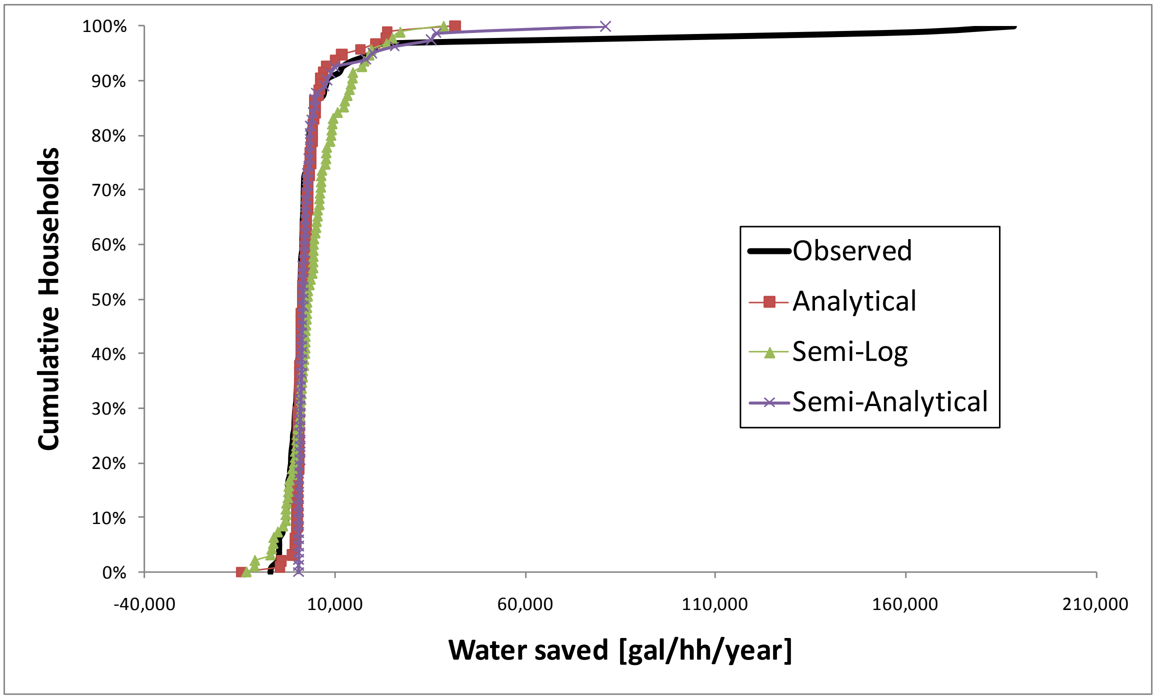


Figure 5. Cumulative distribution among households of water saved by retrofitting faucets.

Three houses located on the tail of the observed distribution of water savings by retrofits (Figure 5), had a very high use before the retrofit compared to the use after (a difference of more than 200 min/hh/day) which are associated with large behavioral change in those households. My belief is that uncommon uses were realized during the study period, or that faucet malfunction in these houses was logged as faucet events rather than leaks.

K-S test results show that the distributions of savings among households predicted by the semi-log and semi-analytical faucet models are similar, while the analytical model is different than the observed distributions (Table 10).

All models do not account for visitors during the study period, a factor that can alter the frequency of use of appliances such as faucets. Water savings by faucet retrofits can be effectively estimated using semi-log and semi-analytical models.

Table 10. K-S test results for faucet models

Model	**K-S Stat (D)**	**Significance (P)**
Analytical	0.250	0.004
Semi -Log	0.156	0.175
Semi-Analytical	0.188	0.077

CHAPTER 6

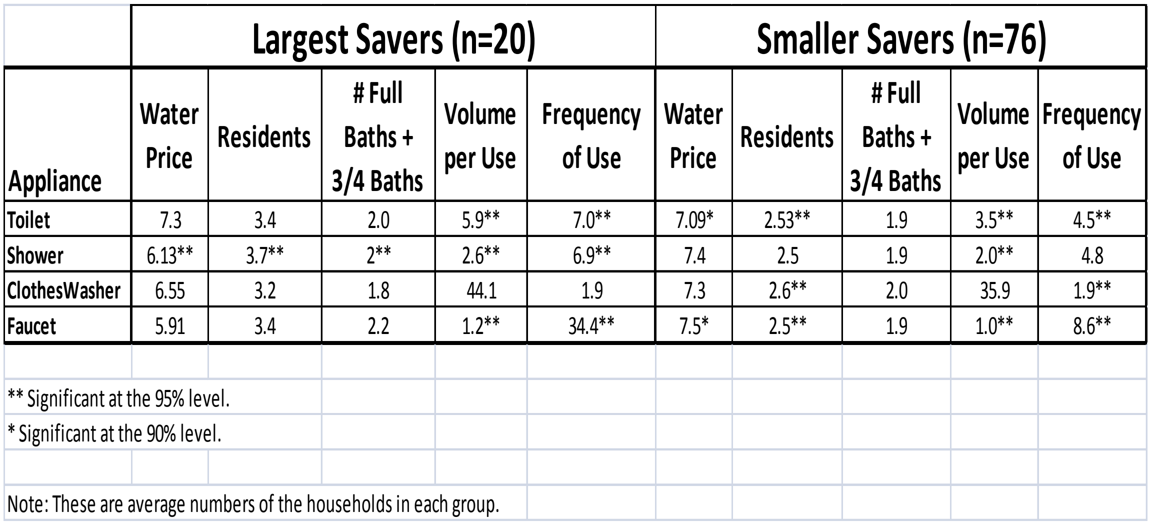
TAIL ANALYSIS

One of the purposes of this study is to identify households with the potential to save more water. These houses are located in the tails of the water savings distributions shown in Figures 2-5. Here we use survey data collected about the houses, to identify characteristics of households that will likely save the most water from retrofits.

To do this, we rank households by water savings for each appliance, then separate the largest 20% savers (20 households) for each appliance from the rest. This breakpoint was chosen to have enough degrees of freedom to run regressions for each group. This segregation also means a certain household could be in the 20% group with highest savings for one appliance, but not for other appliances. Linear regressions were made for each group of households by appliance, using the variables on Table 11 against water savings.

Households that saved the most water retrofitting toilets and clotheswashers had more residents than households that saved less water (Table 11). These two appliances have controlled volume in each of their uses, so the user cannot use a different amount of water with each flush or load of clothes. In case of the toilet, there is a significance difference in the frequency of use (flushes/person/day) between high water savers (7 flushes/person/day) and low water savers (4.5 flushes per person per day). These results show how a high frequency of use combined with a water efficient appliance result in large savings.

Table 11. Comparing characteristics of households that save the most water to households that save less water



	Largest Savers (n=20)					Smaller Savers (n=76)				
Appliance	Water Price	Residents	# Full Baths + 3/4 Baths	Volume per Use	Frequency of Use	Water Price	Residents	# Full Baths + 3/4 Baths	Volume per Use	Frequency of Use
Toilet	7.3	3.4	2.0	5.9**	7.0**	7.09*	2.53**	1.9	3.5**	4.5**
Shower	6.13**	3.7**	2**	2.6**	6.9**	7.4	2.5	1.9	2.0**	4.8
ClothesWasher	6.55	3.2	1.8	44.1	1.9	7.3	2.6**	2.0	35.9	1.9**
Faucet	5.91	3.4	2.2	1.2**	34.4**	7.5*	2.5**	1.9	1.0**	8.6**

** Significant at the 95% level.

* Significant at the 90% level.

Note: These are average numbers of the households in each group.

For shower retrofits, household size was a significant factor that differentiated households that saved the most water from households that saved less water. Also, higher savers used the shower more frequently and, prior to retrofitting, had less efficient showerheads than lower savers.

For faucet retrofits, households that saved the most water had significantly more residents than households that saved less water. As with the showerheads, households that saved the most water used faucets more frequently, and, prior to retrofits, had less efficient faucets than lower savers. Largest savers had more full and three-quarter bathrooms than lower savers, indicating that more appliances had the potential to save more water.

Generally, the largest savers faced lower water prices, although this result was not statistically significant. This result may occur because these households had a lower financial incentive to conserve water prior to the retrofits (price did not change through the study period).

CHAPTER 7

DISCUSSION

Analytical, regression, and semi-analytical regression models have been developed to estimate water savings by retrofitting toilets, showerheads, clothes washers, and faucets. Model results show and separate the effects of technological and behavioral factors on water use and water savings.

The analytical models for toilets, showerheads, and clothes washers perform very well according to the Kolmogorov-Smirnov tests and estimated savings correspond well to observed savings (Figure 6). The analytical model for estimating water saved by retrofitting faucets performs less well and often underestimates water savings.

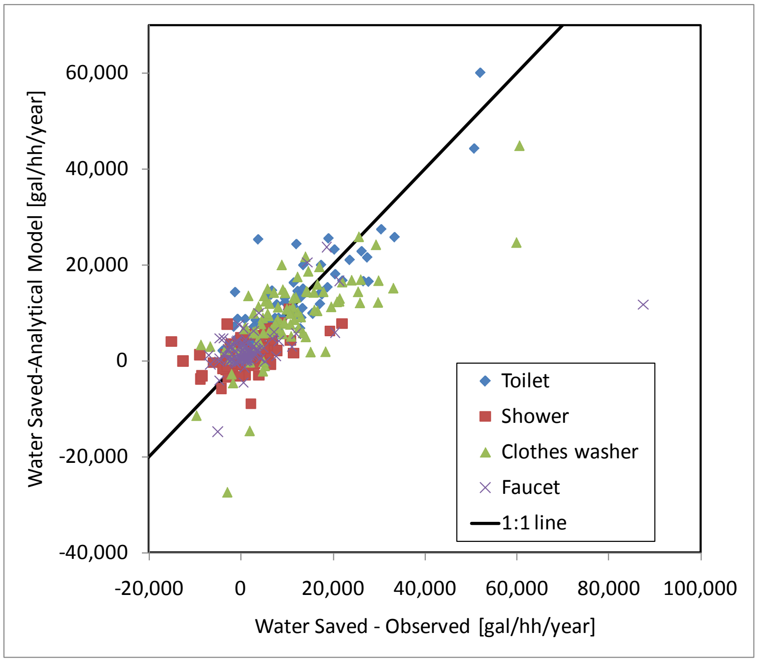


Figure 6. Observed and analytical estimates of water saved by retrofitting toilets, showers, clothes washers, and faucets.

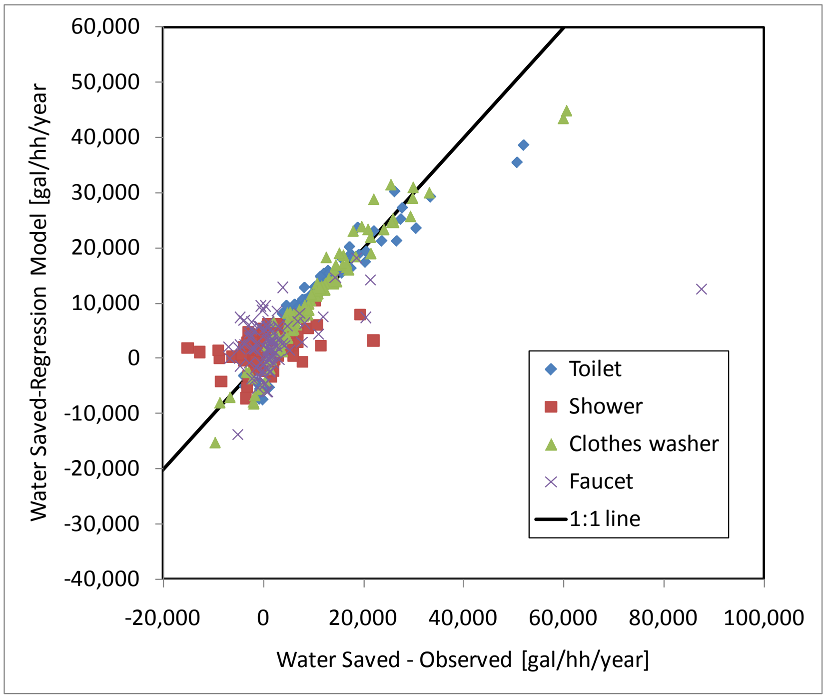


Figure 7. Observed and semi-log regressions estimates of water saved by retrofitting toilets, showers, clothes washers, and faucets.

The regression model estimates better correspond to observed water savings (Figure 7). Most estimated savings are on or very close to the 1:1 line of observed savings. Some households stand out as outliers in both Figures 6 and 7 and suggest that neither model can accurately estimate savings for all households. These outliers have very different frequency of use and or technological performance before and after the retrofits.

Toilets and clothes washers' models worked best. Results show that when the person doesn't have the option of regulating the flow rate used in indoor appliances it's possible to segregate and identify low water savers based on technological and behavioral components. Appliances such as faucets and showerheads, where the user can modify the flow rate at the start and during each use, make estimating savings more difficult since that flow rate can vary significantly on the frequency of use. It's important to point out that the models use as a variable the number of permanent residents, and do not account for visitors during the study period. Unobserved visitors could alter the frequency of appliance uses.

Larger savers faced, on average, lower water prices, than low savers. In general, high savings households had 3.32 residents, compared to 2.5 residents on households that save less water. Also, higher savers used the appliances more frequently and, prior to retrofitting, had less efficient appliances than lower savers.

CHAPTER 8

CONCLUSSIONS AND RECOMMENDATIONS

Analytical, regression, and semi-analytical models to estimate water savings were developed based on detailed, disaggregated water end-use data. Water savings result from a combination of the technology installed in the households and the use of these appliances.

Semi-log regression models performed better than analytical and semi-analytical models, and provide a way to estimate indoor residential water savings based on technological and behavioral components. For all the appliances, technological and behavioral variables such as flow rates, durations, and use frequency are significant. Houses that saved more water had on average more residents than those who saved little to no water. They also used the appliances more frequently and, prior to retrofitting, had less efficient appliances than lower savers.

Although the houses that saved more water had a lower water price on average, this wasn't statistically significant. The number of bathrooms did not show a clear trend, varying this from appliance to appliance; averaging the results the houses that saved more water had 1.93 full bathrooms compared to 1.88 of the rest of the sample.

Study results help improve engineering methods to estimate water savings from retrofits. By calculating water savings with the presented models, utility companies can estimate savings in their region and motivate customers with more residents, less efficient appliances, and high use frequency, to replace old appliances for newer and more efficient ones to conserve water. With these contributions, water conservation programs can save more water with less effort and lower costs.

REFERENCES

Berk, R. A., D. Schulman, M. McKeever, and H. E. Freeman. 1993. Measuring the impact of water conservation campaigns in California. Climate Change 24(3): 233-248.

Buchberger, S. G., and G. J. Wells. 1996. Intensity, duration, and frequency of residential water demands. Journal of Water Resources Planning and Management 122(1): 11-19.

Energy Policy Act of 1992. Public Law 102486, 102nd Congress. Washington, D.C. (Oct. 24, 1992).

Campbell, H., R. Johnson, and L. Hunt. 2004. Prices, devices, people, or rules: The relative effectiveness of policy instruments in water conservation. Review of Policy Research. Volume 21. No. 5.

Chakravarti, I.M, R.G. Laha, and J. Roy. 1967. Handbook of methods of applied statistics. Vol. I. John Wiley and Sons, New York.

Kenney, D. S., C. Goemans, R. Klein, J. Lowrey, and K. Reidy. 2008. Residential water demand management: Lessons from Aurora, Colorado. Journal of the American Water Resources Association 44(1): 192-207.

Michelsen, A. M., J.T. McGuckin, and D. Stumpf. 1999. Nonprice water conservation programs as a demand management tool. Journal of the American Water Resources Association 35(3): 593-602.

Renwick, M. E., and S.O. Archibald. 1998. Demand side management policies for residential water use: Who bears the conservation burden? Land Economics 74(3): 343-359.

Rosenberg, D. 2007. Probabilistic estimation of water conservation effectiveness. Journal of Water Resources Planning and Management 133(1): 39-49.

USEPA 2004. Water and energy savings from high efficiency fixtures and appliances in single family. US EPA Combined Retrofit Report, Vol. 1.

Wallander, S. 2009. Essays on the Economics of Water and Energy Conservation. Unpublished PhD Dissertation. Yale University, New Haven, CT.

Walski, T. M., W.G. Richards, D.J. McCall, A.K. Deb, and J.M. Morgan. 1985. Calculating effectiveness of water conservation measures. Journal of Environmental Engineering-Asce 111(2): 209-221.

Whitcomb, J. 1990. Water use reductions from retrofitting indoor water fixtures. Water Resources Bulletin. 20(6): 921-926.