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Integrated Assessment of Water Conservation Practices For Sustainable Management Strategies

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INTEGRATED ASSESSMENT OF WATER CONSERVATION PRACTICES FOR SUSTAINABLE MANAGEMENT STRATEGIES

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requirements for the degree of

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CIVIL ENGINEERING

By

Mengshan Lee

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To: Dean Amir Mirmiran
College of Engineering and Computing

This dissertation, written by Mengshan Lee, and entitled Integrated Assessment of Water Conservation Practices for Sustainable Management Strategies, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

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The dissertation of Mengshan Lee is approved.

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DEDICATION

This dissertation is dedicated to my wonderful families and friends: particularly to my grandparents, Renyi and Showlan Pan, for their support and encouragement; and to my fiancé, Wenhung Huang, for his patience and understanding during my studies.

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ABSTRACT OF DISSERTATION

INTEGRATED ASSESSMENT OF WATER CONSERVATION PRACTICES FOR SUSTAINABLE MANAGEMENT STRATEGIES

by

Mengshan Lee

Florida International University, 2011

Miami, Florida

Professor Berrin Tansel, Major Professor

Miami-Dade County implemented a series of water conservation programs, which included rebate/exchange incentives to encourage the use of high efficiency aerators (AR), showerheads (SH), toilets (HET) and clothes washers (HEW), to respond to the environmental sustainability issue in urban areas. This study first used panel data analysis of water consumption to evaluate the performance and actual water savings of individual programs. Integrated water demand model has also been developed for incorporating property's physical characteristics into the water consumption profiles. Life cycle assessment (with emphasis on end-use stage in water system) of water intense appliances was conducted to determine the environmental impacts brought by each practice.

Approximately 6 to 10 % of water has been saved in the first and second year of implementation of high efficiency appliances, and with continuing savings in the third and fourth years. Water savings (gallons per household per day) for water efficiency appliances were observed at 28 (11.1%) for SH, 34.7 (13.3%) for HET, and 39.7 (14.5%) for HEW. Furthermore, the estimated contributions of high efficiency appliances for reducing water demand in the integrated water demand model were between 5 and 19%

(highest in the AR program). Results indicated that adoption of more than one type of water efficiency appliance could significantly reduce residential water demand.

For the sustainable water management strategies, the appropriate water conservation rate was projected to be 1 to 2 million gallons per day (MGD) through 2030. With 2 MGD of water savings, the estimated per capita water use (GPCD) could be reduced from approximately 140 to 122 GPCD. Additional efforts are needed to reduce the water demand to US EPA's "Water Sense" conservation levels of 70 GPCD by 2030. Life cycle assessment results showed that environmental impacts (water and energy demands and greenhouse gas emissions) from end-use and demand phases are most significant within the water system, particularly due to water heating (73% for clothes washer and 93% for showerhead). Estimations of optimal lifespan for appliances (8 to 21 years) implied that earlier replacement with efficiency models is encouraged in order to minimize the environmental impacts brought by current practice.

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BMP	Best management practice
EPA	Environmental protection agency
GHG	Greenhose gas
GPCD	Gallons per capita per day
GPHD	Gallons per household per day
GPMD	Gallons per measurement per day
HE	High efficiency
HET	High efficiency toilet
HEW	High efficiency washer
LCA	Life cycle assessment
MDC	Miami-Dade County
mt	Metric tons
MG	Million gallons
SFWMD	South Florida Water Management District
SH	Showerhead
SLIFR	Senior and Low Income Full Retrofit
MDWASD	Miami-Dade Water and Sewer Department
WD	Water demand

CHAPTER I

INTRODUCTION

Water management consists of water policies that seek to maintain steady and dependable community water supplies for multiple purposes. The water demand management strategies can be broadly divided into three major categories: economic, technological and behavioral (Saurií, 2003). In traditional water management, high flows of water are captured during wet seasons, and stored in reservoirs to supplement water supplies at drier times, thereby maximizing the reliability of water supplies and certain economic benefits each year (Richter et al., 2003). However, population growth, economic expansion, climate and lifestyle changes have adversely increased stress on future water resources (Arnell et al., 2011; Mohamed, 2000; Postel et al., 1996). Therefore, environmentalists are directing water management towards sustainable management practices (Wong and Brown, 2009). This implies that aggressive and continual developments in sustainable water management should be defined, refined and modified to meet environmental sustainability criteria.

Sustainable water management is a critical issue from environmental, social and economic perspectives. Water utilities are facing challenges for developing adequate water services with conservation budgets (Hildebrand et al., 2009) while new technologies or practices usually require experiments and frameworks to accommodate the complexity and uncertainty (Farrelly and Brown, 2011). The concerns of increasing needs in water demand management not only because of limited water resources but also because of the environmental impact (for instance, greenhouse gas emissions) attributed to water system operations (Fidar et al., 2010).

Water demand can be affected by demand management strategies such as pricing, water metering, water restriction, education campaigns and water conservation practices. Water conservation practices, in this study, are defined as implementation of high water use efficiency appliances to ensure that lower water demand can be achieved. The water conservation practices usually are designed for residential households based on economic, social and environmental factors. Therefore, residential water demand is expected to undergo substantial changes in the near future (Schleich and Hillenbrand, 2009).

Successful implementations of water conservation practices have been reported in the USA (Mayer, et al., 2004) and Australia (Turner et al., 2004, Willis et al. 2010). The participants were estimated to have more than 35 percent of indoor water savings from replacement of high efficiency appliances (showerhead, faucet, aerator, toilet and clothes washer). Of all the appliances, toilets and clothes washers are shown to have the greatest potential in conserving indoor water use (Inman & Jeffery, 2006).

Targeting water conservation practices for residential customers is beneficial due to several facts: 1. majority of water demand in a community comes from residential customers, 2. residential appliances create a significant percentage of household water demand, and, 3. the potential water savings for water efficiency appliances is well acknowledged (Balbin et al., 2010; Baumann et al., 1998; Fidar et al., 2010; Kenney et al., 2008; Lee et al., 2010; Millock and Nauges, 2010; Olmstead and Stavins, 2009). Moreover, water efficiency appliance incentives (i.e., rebate or exchange programs) are considered to be more acceptable by the public in comparison to other water management policies such as price increase or water restrictions (Millock and Nauges, 2010; Randolph and Troy, 2008).

1.1 Background of Study Site: Miami-Dade County, Florida

Miami-Dade County is an urban area located in the southeastern part of the Florida State in the USA and it is ranked as the most populous county in Florida and eighth-most populous county in the USA according to US Census Bureau (2009). Miami-Dade County is also named as the second largest county in Florida in terms of land area (1,525,090 acres). The historical population trends show that Miami-Dade County experienced an exponential growth during 1900-2000 and a steady growth after 2005 as shown in Figure 1.1. As population increased, the number of retail water customers from Miami-Dade Water and Sewer Department increased from about 370,000 in 2000 to 420,000 in 2008 as presented in Figure 1.2. The recent trends showed that both population and number of water customers have consistently increased by about 0.15% to 1.5% every year. These increases are primarily due to urban development and migration to the County.

1.2 Historical Water Demand Profile of Miami-Dade County

Water use trends from 2000 to 2008 for Miami-Dade County are presented in Figure 1.3. The total water produced includes annually water demands to retail customers, wholesale customers and non-account sources, which are dark grey, light grey and black bars in Figure 1.3, respectively. Retail and wholesale customers are classified by different municipalities. Among the 35 municipalities in Miami-Dade County; only Hialeah, Miami Beach, North Miami, North Miami Beach, Opa-Locka, Miami Springs, Hialeah Gardens, Bal Harbour, Medley, Bay Harbor Islands, Surfside, North Bay Village, West Miami, Indian Creek Village and Virginia Gardens are wholesale customers. Adding up the water use for the wholesale and retail customers gives average total water sold of about 100 billion gallons per year during the period from 2000 to 2008 period.

Although the census data indicates that the population and the number of customers in Miami-Dade County increased over time, the water demand data does not follow the same trends. The total water demand first dropped in 2001, and increased to higher levels during 2002 and 2006. The first drop was due to the water use restriction enforced by South Florida Water Management District (SFWMD). Another significant drop started from 2006 and it could be partially due to the success of the BMPs implemented by MDWASD.

Historical daily water demand (million gallons per day, MGD) and per capita water use (gallons per capita per day, GPCD), from 1994 to 2008 are presented in Figure 1.4 and 1.5, respectively. The per capita water use was calculated by dividing total water usage by total population. Both water demand and per capita water use follows the same trend as the total water demand (Figure 1.3). This informs that the increase in population did not result into a proportional increase in water use. Before 2001, the per capita water uses were all greater than 160 GPCD; starting 2001, the per capita water use fluctuated between 156 to 160 GPCD. A remarkable drop in per capita water use was found in 2007, which reduced the water use from 156.5 to 139.9 GPCD.

Percent changes in per capita water use are shown in Figure 1.6. The number above the bar indicates percent changes in per capita water use, and the arrows points the specific year at which the BMPs for water conservation were implemented by Miami-Dade County. The positive numbers before 2001 implied that there was an increase of public awareness of water conservation during the period. The fluctuation between 2002 and 2004 can be expressed as adjustment period of water restriction by SFWMD. The implementation years for showerhead (SH), high efficiency toilet (HET) and high efficiency clothes washer (HEW) programs were 2005, 2006, and 2007, respectively. The most significant water savings occurred in 2001 and 2007. The water savings observed in 2007 was partially due to collective impact of BMPs implemented.

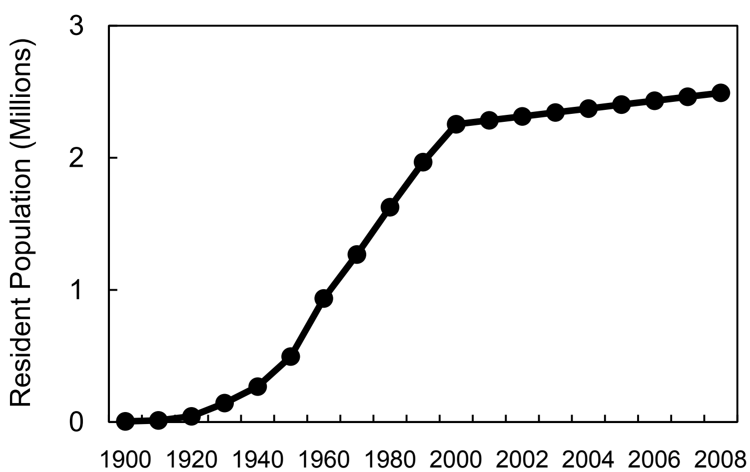

Figure 1.1 Increase in population of Miami-Dade County during 1900-2008

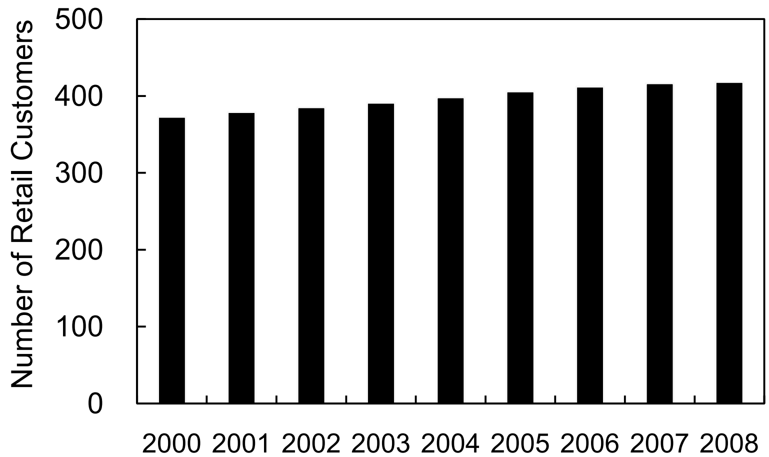

Figure 1.2 Increase in retail water customers (in thousands) in Miami-Dade County during 2000-2008

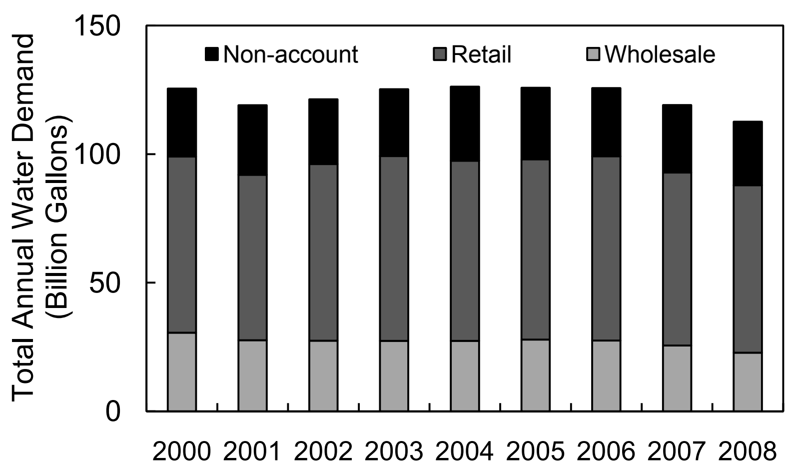

Figure 1.3 Historical total annual water use from 2000 to 2008

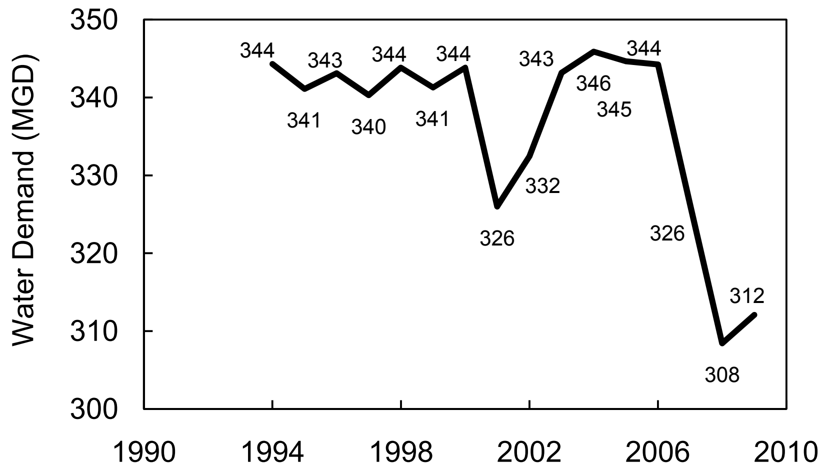

Figure 1.4 Historical daily water demand (million gallons per day)

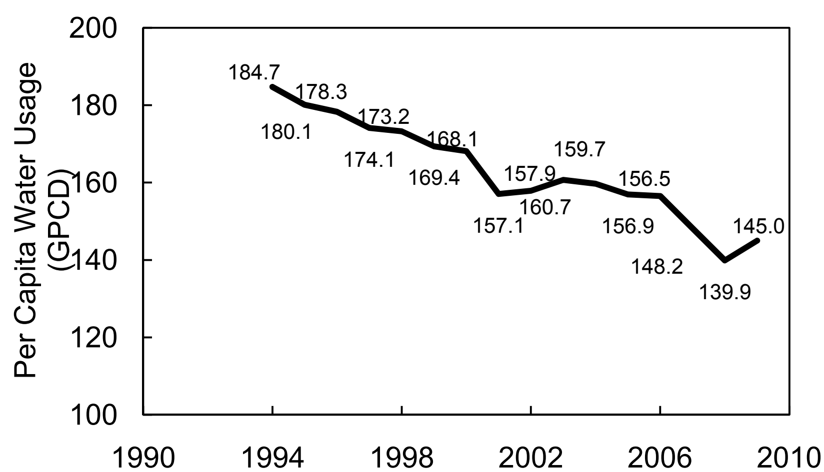

Figure 1.5 Historical per capita water use from 1994 to 2009

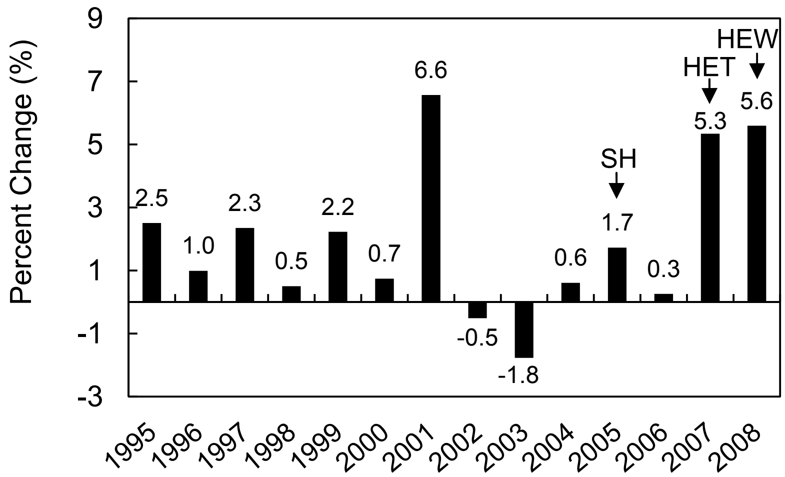

Figure 1.6 Percent change in per capita water use

1.3 BMPs Program Description

Best management practices (BMPs) for water conservation considers all the uses of water and maximizes conservation. The Federal Energy Management Program recommended fourteen BMPs regarding water conservation includes: water management planning, information and education programs, distribution system audits, leak detection and repair, water-efficient landscaping, water-efficient irrigation, toilets and urinals, faucets and showerheads, boiler/steam systems, single-pass cooling systems, cooling tower systems, commercial kitchen equipment, laboratory/medical equipment, alternate water sources and other water use (USEPA, 2010).

The BMPs selected by MDWASD include high efficiency showerheads (SH), toilets (HET) and clothe washers (HEW). These three appliances are high water use units among all the indoor water use fixtures. Showers account for 16.8%, toilets account for 26.7%, and clothes washers account for 21.7% of indoor per capita water use (Mayer et al., 1999). Table 1.1 compares the water use of high efficiency appliances selected for BMPs by MDWASD with traditional ones (Vickers, 2001). MDWASD requires the customers to purchase high efficiency units which are included in US EPA Water Sense Labeled list.

These programs were promoted in different years, 2005 for SH, 2006 for HET and SLIFR, and 2007 for HEW. The maximum quantity of appliance adoption is two for SH and HET programs and one for HEW program. The HET participants have average 1.2 toilets and the SH participants have average 1.3 showerheads.

1.3.1 Showerhead and Retrofit Kit (SH) Exchange Program

Traditional showerheads have typical flow rates between 2.2 and 8 gallons per minute (GPM). The high efficiency showerheads provided by MDWASD use only 1.5 GPM. Assuming a showering time of 8 minutes, the high efficiency showerheads would use about 12 gallons while traditional showerheads would use more than 17.6 gallons. Water use during showering could be reduced by 32% in 8 minutes at shower bases.

In showerhead exchange program, MDWASD offered high efficiency showerhead (1.5 gallons per minute) and equipped with on/off valve and swivel head for user comfort and convenience. A retrofit kit with two high efficiency aerators is included in the showerhead exchange package. The showerhead and retrofit kits are available for free exchange of the traditional ones.

1.3.2 High Efficiency Toilet (HET) Rebate Program

The US EPA Water Sense program requires high efficiency toilets to provide less than 1.28 gallons of water per flush (GPF) than traditional ones (greater than 1.6 GPF). This would translate to 20% less water use per flush. Toilets in the water conservation program could also be dual flush systems with 1.6 GPF and 0.8 GPF for solid and liquid wastes, respectively. Eligible residents receive a rebate of up to $100 USD as an incentive to join the program.

1.3.3 High Efficiency Clothe Washer (HEW) Rebate Program

National average for clothes washer load volume is 40.9 gallons per load (GPL). Typical range is from 40 GPL to 45 GPL. For high efficiency clothes washers, the water use between 20 GPL and 25 GPL. Up to 50% water savings could be accomplished by installing high efficiency clothes washers. Eligible residents receive a rebate of up to $150 USD as an incentive to join the program.

1.3.4 Senior and Low Income Full Retrofit Program (SLIFR)

Senior families have been selected to participate in the water conservation program are customers with low income seniors as reflected in their property tax exemptions. The senior single family residents identified were retrofitted with one high-efficiency toilet, maximum two high-efficiency showerheads comes along with showerhead kits and aerators. The water use for each high efficiency appliances are same as described in the previous sections (1.3.1 and 1.3.2) and listed in Table 1.1. The program started in late 2006 and has been continuing.

1.4 Hypotheses and Objectives

This study, in general, is to have an integrated assessment of potential environmental benefits by implementation of water conservation practices. Thus, this dissertation is built based on the following four specific hypotheses:

1. Are the proposed water conservation practices effective in terms of water savings and other environmental impacts?
2. Can the proposed water conservation practices be applied as a determinant in controlling residential water demand?
3. Can the proposed water conservation practices reduce the overall environmental impacts?
4. Can the proposed water conservation practices be recommended as sustainable management strategies?

Three major objectives are developed to test the hypotheses described above, which include the following:

1. To evaluate the effectiveness of water conservation practices by quantifying actual water savings and observing changes in water use profile.
2. To assess the impacts from economic, environmental and social determinants in affecting residential water demand.
3. To determine the benefits of implementation of water conservation practices from life cycle assessment point of views.

1.5 Scope of the Dissertation

The goal of this study is to have an integrated assessment of the potential benefits to the environment sustainability of water conservation practices, based on their actual performance. Sustainable management strategies can be advised based on the results from this assessment. The following brief descriptions of the four major chapters, explain the objectives and methodologies used in developing this study.

Chapter II, entitled "RESIDENTIAL WATER DEMAND TREND SHIFTS BY WATER CONSERVATION PRACTICES: A FOUR YEAR STUDY", uses panel data analysis to evaluate long-term actual water savings and trend shifts due to implementation of water use efficiency appliances. This paper aims to replace currently used estimates, with real observations of water savings through water conservation practices based on actual consumption data from individual households. Effects of type and number of high efficiency appliances on water savings are also discussed. The analysis can be useful for determining performances and affecting time-lapse of individual appliance.

Chapter III, entitled "GOAL BASED WATER CONSERVATION PROJECTIONS BASED ON HISTORICAL WATER USE DATA AND TRENDS IN MIAMI-DADE COUNTY", presents water savings projections using specified water conservation goals. The water conservation goals were defined as percentage savings per year, estimated water conservation quantities in daily water demand, and targeted per capita water use to achieve desired water conservation goals. The main objectives of this study are to project the future water demand from a demand side management point of view, and to understand the corresponding water demand changes from implementation of water conservation practices in Miami-Dade County through 2030. The historical population and water demand data collected in this study can also provide necessary baseline for future water demand management studies.

Chapter IV, entitled "INTEGRATED RESIDENTIAL WATER DEMAND MODEL INCORPORATING WATER CONSERVATION PRACTICES", develops a descriptive residential water demand model to analyze the effects of water conservation practices on water demand. The model facilitates simple ordinary least square equation calibrated with detailed household-level consumption data and several water-related social determinants. Determinants considered in the model were grouped into four categories as property characteristics, household composition, weather variables and adoption of water conservation practices. The main objective of this study is to identify the key contributing factors on water demand changes. Accordingly, sustainable water demand management can be improved by targeting to specific groups.

Chapter V, entitled "RESIDENTIAL WATER CONSERVATION PRACTICES: LIFE CYCLE ASSESSMENT OF DEMANDS AND EMISSIONS", evaluates environmental impacts of energy and water demand and greenhouse gas emission from three residential water-intense appliances using the life cycle assessment (LCA) approach. The LCA analysis includes stages from raw material production, manufacturing, end-use and demand and end-of-life disposal. The assessment especially focuses on hidden consumption and environmental impacts from end-use and demand phases within the water system. Water-related activities such as water supply, water heating and wastewater treatment are also considered in the LCA. Optimal lifespan for appliances using energy consumption balance approach minimize the environmental impacts brought by a product. The LCA and lifespan optimization can provide essential information in minimizing the environmental impacts from a practice by reducing resource consumption, pollution emission and waste generation.

CHAPTER II

RESIDENTIAL WATER DEMAND TREND SHIFTS BY WATER CONSERVATION PRACTICES: A FOUR YEAR STUDY

(Mengshan Lee, Berrin Tansel, Maribel Balbin,

submitted to *Resources, Conservation and Recycling*)

2.1 Introduction

Implementation of water conservation practices has been widely adopted in developed countries and regions for sustainable water demand management purposes. One of the water conservation practices is the installation of water efficiency appliances in residential units. Targeting water conservation practices for residential customers is beneficial due to several facts: 1. majority of water demand in a community comes from residential customers, 2. most of the residential appliances share significant amount of household water demand, and, 3. the potential water savings for water efficiency appliances is well acknowledged (Balbin et al., 2010; Baumann et al., 1998; Fidar et al., 2010; Kenney et al., 2008; Lee et al., 2010; Millock and Nauges, 2010; Olmstead and Stavins, 2009). Also, water efficiency appliance incentives (i.e., rebate or exchange programs) are considered to be more acceptable by public in comparison to other water management policies such as price increase or water restrictions (Millock and Nauges, 2010; Randolph and Troy, 2008).

Location, function and personal preferences are major factors in determining water demand. Residential water use could be classified as indoor and outdoor water use. Generally, approximately 50 percent of the residential water is for indoor use. The top three water consuming indoor fixtures include toilets, showerheads and washers, which account for 26.7%, 16.8% and 21.7% of total indoor consumption, respectively (Mayer et al., 1999). Residential water demand is affected by demand management strategies such as water metering, water restriction and installation of water efficiency appliances. Table 2.1 summarizes the estimated water savings reported for water conservation appliances. However, most of the water savings in water conservation appliances are estimated by certain assumptions with aggregated data. Therefore, estimation of actual water savings for each water conservation practice is essential for water demand planning.

This paper aims to fill the gap (estimates versus observations) of water savings through water conservation practices based on water demand data from individual households. Water demand trend shifts and frequency diagrams were studied for water conservation programs. Variability in water demand data such as low and high end users, and due to seasons and type of appliances were evaluated.

Table 2.1. Estimated water savings from residential water conservation appliances

Study	Water conservation practices	Water savings[a]
Willis et al., 2010	Alarming visual display shower monitor	4.1
Davis, 2008	High efficiency cloth washer	19.6
Reidy and Tejral,	Low-flow toilet (1.6 gallon/flush or less)	26.2
2008	High efficiency cloth washer	30.9
Mayer et al., 2004	Ultra low flush toilet (1.6 gallon/flush or less)	29.4
	High efficiency showerhead (less 2.5 gallon/minute)	10.2
	Front loading horizontal axis cloth washer	20.1
	Faucet with aerator, sensor and hand free controllers	9.3

[a] GPHD, gallons per household per day

2.2 Methodology

In this study, only participants who joined the program in the first year of implementation are included for long term analysis. Water conservation program participants (N=1829) in this study were recruited from the MDWASD water conservation website (http://www.miamidade.gov/conservation/). The study group includes single family residents only. A period of four years of seasonally/monthly household water demand data from January 2006 to December 2009 were used in this study. This period covered the time period for implementation of various programs. In order to differentiate the water demand levels or degree of water savings, water demand determinants were defined as the follows:

1. Household water demand: water consumption in the household expressed as gallons per household per day (GPHD);
2. Mean household water demand: average of daily household water demand;
3. Per capita water use: water use in gallons per capita per day, GPCD, using household size in HET program (3.1 people per household);
4. Low user water demand: average of water demand for 10% of consumers in lower water usage range;
5. High user water demand: average of water demand for 10% of consumers in higher water usage range;
6. Percent change or water savings in water demand: ratio of water demand difference between target year and base year to water demand in base year.

2.3 Results and Discussions

Miami-Dade County has experienced significant decrease in water demand since 2005 which is partly due to the effectiveness of water conservation plan. Figure 2.1 presents the historical water demand trends for participants in water conservation programs which include high efficiency washers (HEW), high efficiency toilets (HET) and high efficiency showerheads (SH). Household water demand for the participants ranged from 200 to 310 GPHD, which corresponds to per capita water use of 65 to 100 GPCD. It is interesting to see that the water demand trends for the customers in these three programs were almost parallel during the early stage (before 2006), but the demand for the customers in the HET program began to drop significantly after 2007. This suggests that participants in HET program have experienced significant water savings after installation of HET.

Climate variables can also influence water demand by altering soil water availability and evaporation rate (Fox et al., 2009; Goodchild, 2003). Miami-Dade County has subtropical climate which could be divided into two major seasons as dry and wet. The seasons in Florida are determined by both precipitation and temperature. The wet season is from May to October which includes months with warm temperatures and significant rainfall. The dry season is from November to April with mild to cool temperatures and low precipitation. Therefore, the water demand in Miami-Dade County could show seasonal effects.

As shown in Figure 2.2, during the four years of study period, significant differences in water demand between dry and wet seasons were observed at 95% confidence level. In 2006, the South Florida Water Management District initiated water

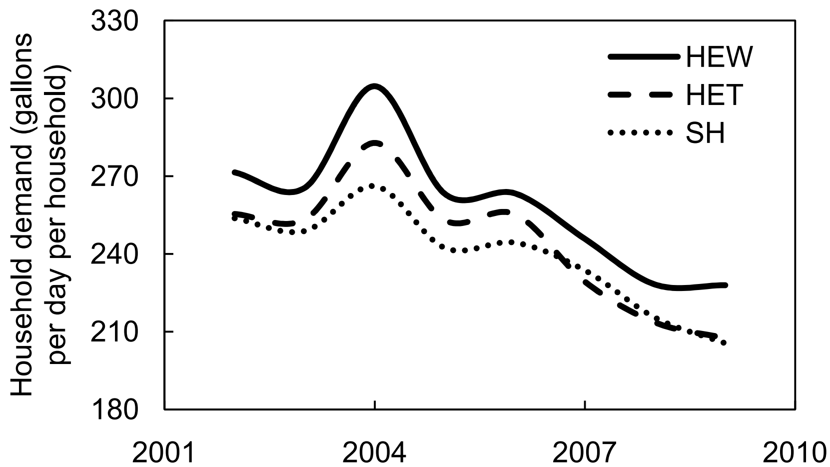

Figure 2.1 Household water demand for water conservation program participants

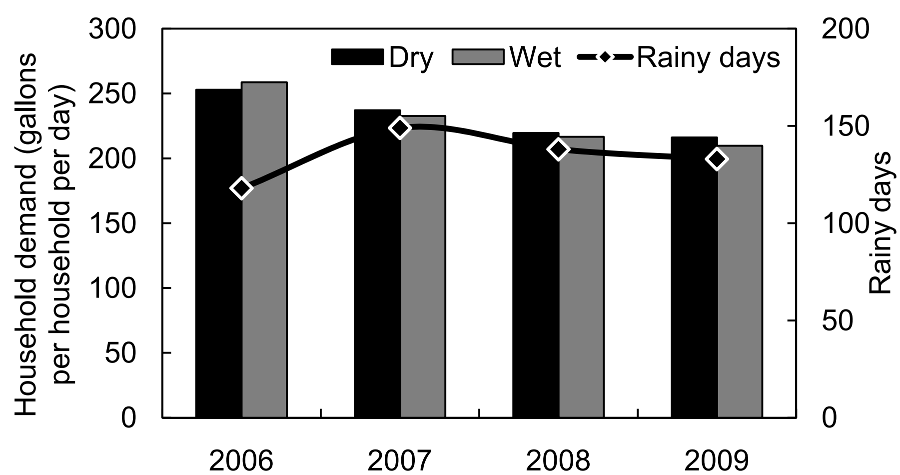

Figure 2.2 Differences of household water demand during dry and wet season

restrictions during wet season, therefore, the water demand during wet season dropped significantly from 2006 to 2007. Combination of water restrictions (focusing on outdoor irrigation systems) and indoor water efficiency appliances replacement programs started in 2006 significantly reduced the household water demand each year. The dramatic drop could also be explained by the increase in number of rainy days (118 to 149 days/year).

2.3.1 Effects of High Efficiency Appliances

High water use efficiency appliances have been well acknowledged for their impact on reducing residential water demand. Pressure-assist is the key mechanism for high efficiency toilets and showerheads that increase flush velocity or boost volume of water. The high efficiency cloth washers are usually designed in horizontal axis that consume less water than vertical axis ones.

Detailed household water demands for the participants in each water conservation program are presented in Table 2.2. The numbers in parenthesis are percent changes in water demand from the previous year. The high and low users are defined as the 10% of customers that are in high or low water use range. A series of paired sample t-tests (assuming equal variance) were performed to determine if changes in water demand are statistically significant at the 95 percent confidence level. An asterisk sign after parenthesis represents there is no statistically significant difference in water demand in present year and previous year at 95 percent confidence level.

Average water demands for both programs were in the range of 250 to 270 GPHD in the base year and in the range of 200 to 255 GPHD in subsequent years. High and low water users were in the range from 500 to 600 GPHD and from 55 to 90 GPHD,

Table 2.2 Household water demand in water conservation practice rebate programs

Water conservation practices	Base Year[d]	1st Year	2nd Year	3rd Year	4th Year
SH (Showerhead, n=421)					
Mean (GPHD[a])	266.1	242.3(-9.0)	244.3(0.9)*	233.6(-4.4)	215.4(-7.8)
High user[b] (GPHD)	687.5	582.1(-15.3)	593.0(1.9)	562.5(-5.1)	525.5(-6.6)
Low user[c] (GPHD)	70.3	61.6(-12.4)	70.6(14.6)	60.8(-13.9)	54.7(-10.0)
HET (Toilet, n=744)					
Mean (GPHD[a])	252.9	255.3(1.0)*	229.2(-10.2)	213.6(-6.8)	207.5(-2.8)
High user[b] (GPHD)	554.4	562.6(1.5)*	493.1(-12.4)	477.9(-3.1)	460.0(-3.7)*
Low user[c] (GPHD)	81.6	79.9(-2.1)*	69.4(-13.2)	64.7(-6.7)	64.8(0.1)*
HEW (Washer, n=664)					
Mean (GPHD[a])	262.8	245.8(-6.5)	225.5(-8.3)	224.1(-0.6)*	N/A
High user[b] (GPHD)	583.3	565.2(-3.1)*	507.5(-10.2)	499.7(-1.5)	N/A
Low user[c] (GPHD)	87.2	78.5(-9.9)	76.8(-2.3)*	87.2(13.6)*	N/A

[a] GPHD stands for gallon per household per day
[b] high user stands for consumers in higher 10% of water use range
[c] low user stands for consumers in lower 10% of water use range
[d] base year stands for one year prior to first year of implementation
* not a statistically significant difference from the previous year at the 95 percent confidence level

respectively. It was observed that both household water demands had significant decrease during the first two years of implementation, and there were still additional savings in the third or fourth year of implementation. It can be concluded that after 2 years, customers get used to the water efficient appliances and additional savings in subsequent years become less significant (Lee, et al., 2010).

In general, about 6 to 10 % water could be saved in the first or second year of retrofit. With the installation of high efficiency appliances, the water demand could be potentially reduced to less than 210 GPHD (approximately equals to 70 GPCD). Similar water savings could be accomplished by both high and low water use consumers. For example, high users could reduce their water demand from over 222 GPCD (base year) to

188 GPCD (first year) by installing high efficiency showerheads. The variation of household water demands could be explained by the differences in family composition and their life style (i.e., frequency of use of water-demanding appliances or activities).

Among all three programs, customers in the HET program had the lowest water demand. The water demand did not change significantly during the first year of retrofit, however, a significant savings (-10.2%) were observed in the second year of retrofit. This could be explained by the fact that toilet accounts for the highest percentage of in indoor water use. Also, toilets are considered are likely source of water leaks due to faulty installation. Thus, replacement of older toilets with HET not only saves water during each use but reduces the water loss due to leaks (Inman and Jeffrey, 2006).

The average annual wash cycle per household in the USA is 289 times (Pakula and Stamminger, 2010). Therefore, use of HEW could save significant amount of water. For the HEW program, the water savings in the first and second years of retrofit were 6.5% and 8.3%, respectively. The water savings detected in the first two years implies that customers were still in transition getting used to the new appliances. For instance, total washing frequency may be increased after receiving a new machine (Davis, 2008). No significant differences in water demand were observed in the third year of retrofit. This suggests that the effects of clothes washer on conserving water remained stabilized after two years.

Water use for showering may have smallest variation because people take showers regularly (Domene and Sauri, 2006). For the SH program, the water savings fluctuated (4.4% in third year and 7.8 in fourth year) over time. Offsetting behaviors such as awareness of water conservation but using more water could be seen in the SH program participants (Inman and Jeffrey, 2006). This phenomenon helps us to address the least water savings found in SH program (Table 2.3). Even though SH saves less water than other appliances, the water savings for SH can still contribute to a certain amount of reduction in energy consumptions and greenhouse gas emissions from water heating (Fidar et al., 2010; Willis et al., 2010).

Comparison of water demands and savings for participants in different programs are listed in Table 2.3. Observed water savings were found to be the largest for the costumers in the HET (39.7 GPHD) programs, followed by HET (34.7 GPHD) and SH (28.0 GPHD) programs. The observed water savings are in same order as the estimated savings presented in Table 2.1, however, with higher magnitudes (approximately 10 GPHD). In urban areas, higher household density, higher number of occupants living in a household can create more opportunities in conserving water. Affluent people may be more aware of benefits of conserving water so that contribute to higher water savings. As demonstrated in Table 2.3, the results are similar to those observed by other studies (Inman and Jeffrey, 2006; Proença and Ghisi, 2010) that toilets and washers have the highest potential in conserving water. In a life cycle assessment study of various types of high efficiency toilets, low flush system toilets (the type most used in MDC) was considered to be an effective option from investment and environmental performance perspectives (Anand and Apul, 2011). High efficiency washers also been valued as potential household goods that reduce water and energy consumption dramatically (Davis, 2008). Table 2.3 also provides estimated annual water savings for 1,000 participants in each program as 10.2, 12.7 and 14.5 million gallons for SH, HET and HEW programs, respectively.

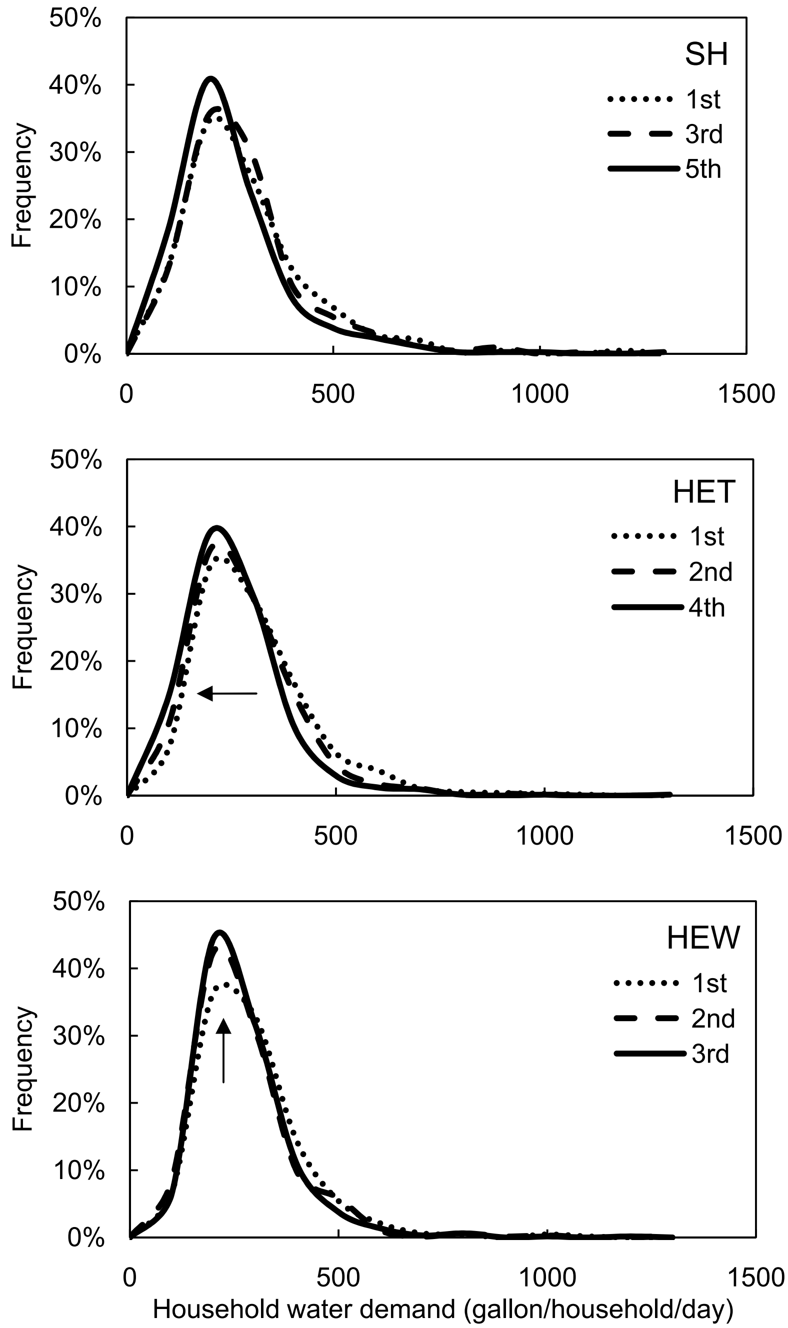

Figure 2.3 Shifts in water demand of residences in the high efficiency appliance programs

Table 2.3 Differences of water demand and savings with and without conservation practices

Parameter	SH	HET	HEW
Mean water demand (GPHD, gallons per household per day)			
Without water conservation practices	252.7[a]	261.1[a]	273.6[b]
With water conservation practices	224.7[c]	226.4[c]	233.9[d]
Water savings (gallons per household per day)	28.0	34.7	39.7
Water savings (%)	11.1	13.3	14.5
Water savings (million gallons per year)[e]	10.2	12.7	14.5

[a] from 2002 to 2005
[b] from 2002 to 2006
[c] from 2006 to 2009
[d] from 2007 to 2009
[e] based on 1,000 customers

Relative frequency diagrams of water demand for participants in the three programs are illustrated in Figure 2.3. The frequency distribution curves for HET and HEW programs show that the water demand distribution either shifted to the left (i.e., water demand decrease) or peak shifted to lower water use range. This suggests that consumers in these programs have continued to reduce their water demand over the years. Meanwhile, the distribution curves are wide and overlapping for the first and third years in the SH program. The overlapping curves could be due to similar water demand observed during these years; which is consistent with the results presented in Table 2.2.

Effects of SH on water savings was observed to be more significant after the third year of implementation. Therefore, a sharp frequency curve toward to lower demand levels was observed (Figure 2.3). This finding suggests offsetting behavior for the customers in the SH program in the first two years of implementation. However, these effects may decrease with year of implementation, thus, resulting in increased water savings.

According to United States Environmental Protection Agency (US EPA) water sense program, an inefficient water use (without conservation) can be defined as water use greater than 70 GPCD. Based on the US EPA definition, the consumers with high water use rates account for 60-70% of all the customers in Miami-Dade County.

2.3.2 Effects of Type and Number of Appliances

There are some customers (85 out of 1829, approximately 4.6%), who participated in more than one type of water conservation programs (multiple type participants). As shown in Figure 2.4, there is significant difference in water demand between participants with one type and multiple types of high efficiency appliances. Household water demand stayed stable in 2005 to 2006 and started to decrease in 2007. The first two years (2005 and 2006) of stable period represented the transition stage when the customers were adjusting to the water conservation appliances and awareness. Preferences for water-intensive or water-conserving lifestyle are typically depend on individuals (Gottdiener, 2000).

The water demand difference between the customers who had one type and multiple types of high efficiency appliances increased over time (Figure 2.4). The demand difference was 40 GPHD in 2005 and increased to 70 GPHD in 2009. The gap for customers with multiple types of high efficiency appliances is much larger than that for one type customers (maximum of 25 GPHD, Table 2.2). This suggests that customers with more than one type of high efficiency appliance can significantly reduce their household water demand. This result was also validated by the frequency density curves (Figure 2.5). The distribution for customers who had no high efficiency appliances is

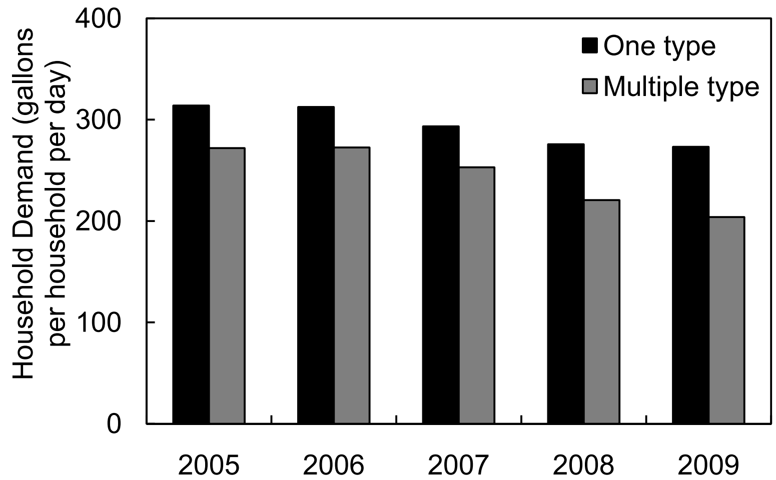

Figure 2.4 Comparison of water demand of participants with only one type and multiple types of water conservation appliances

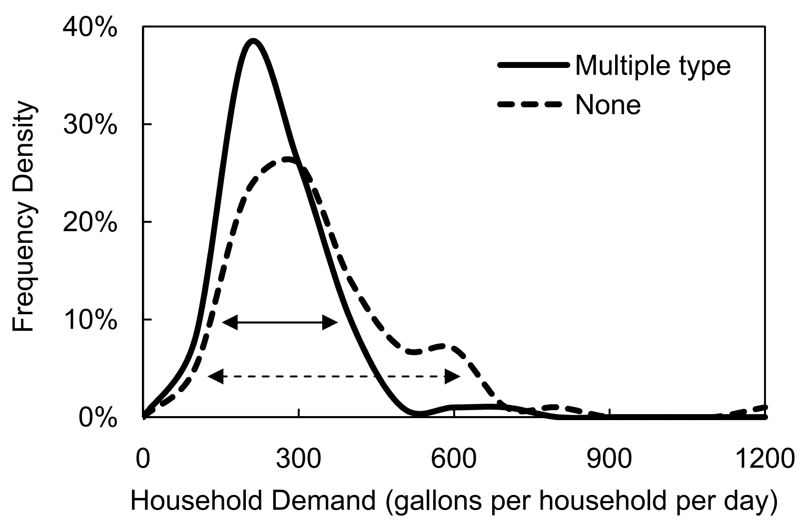

Figure 2.5 Frequency density curve for customers with no (dash line) and multiple types (solid line) of appliances

wide with high demand range. On the other hand, the trend for customers who had multiple high efficiency appliances is sharp and shifted towards the lower demand range. With the increasing number of residents joining the high efficiency appliance rebate programs (3478 in HET, 938 in HEW and 4293 in SH as in 2009), it is expected to see more residents with multiple types of high efficiency appliances. Urban area lifestyle may also facilitate these residents becoming more aware of benefits of water conservation and high efficiency appliances.

2.3.3 Senior and Low Income Full Retrofit

The senior and low income full retrofit (SLIFR) program started in 2006. The changes of water use for SLIFR program participants are included in Table 2.4. The water consumption for this study group ranged from 150 to 200 GPHD, which is much less than that for regular families (207 to 266 GPHD, Table 2.2, and Figure 2.6). This can be due to the difference of family composition (i.e., number of people) and their life style (have less water-demanded appliances or activities).

For the SLIFR families participating in the full retrofit program, the average water consumption was reduced from 203.9 GPHD in 2005 (base year) to 149.7 GPHD in 2009 (fourth year). As shown in Table 2.4, high users (the customers who constitute the top 10% of the highest water use) in this group have reduced their average water use from 520.3 GPHD to 435.0 GPHD. Low users (the customers representing the 10% lowest water use) also reduced their average water consumption from 54.5 GPHD to 32.3 GPHD. In comparing the water use in base year (2005) to different implementation years, the overall water use decreased by 3.2% in first year and by 16.1% in the third year of retrofit. The data exhibits that the water savings in the first year (2006) was not significant perhaps during the first year of implementation, and the customers needed to adjust to new appliances and change their water use habits (Balbin et al., 2010).

Figure 2.7 presents frequency trend shifts in household water demand for SLIFR customers. The water use profile displays distributions with a peak water use at 200 GPHD in the first two years of retrofit, and with peak water use around 100 to 200 GPHD in the last two years of retrofit. The overlapping curves (found in the first and second year) could be due to similar water demand observed during these years; which is consistent with the results presented in Table 2.4. Water savings for SLIFR customers was observed to be more significant in the third year of implementation. Therefore, a sharp frequency curve toward to lower demand levels was observed (Figure 2.7). This suggests that majority of the customers observed savings in water use. Also, as shown in Table 2.4 and Figure 2.6, the trend shifts implies that the program participants have continued to reduce their water demand over the years.

Table 2.4 Household water demand in senior and low income full retrofit program (n=271)

Parameter (GPHD)	Base Year[d]	1st Year	2nd Year	3rd Year	4th Year
Mean	203.9	197.4(-3.2)	184.9(-6.3)	155.1(-16.1)	149.7(-3.5)
High user[b]	520.3	512.7(-1.4)	479.6(-6.5)	433.1(-9.7)	435.0(0.4)
Low user[c]	54.5	51.6(-5.3)	48.7(-5.7)	37.6(-22.6)	32.3(-14.1)

[a] GPHD stands for gallon per household per day
[b] high user stands for consumers in higher 10% of water use range
[c] low user stands for consumers in lower 10% of water use range
[d] base year stands for one year prior to first year of implementation

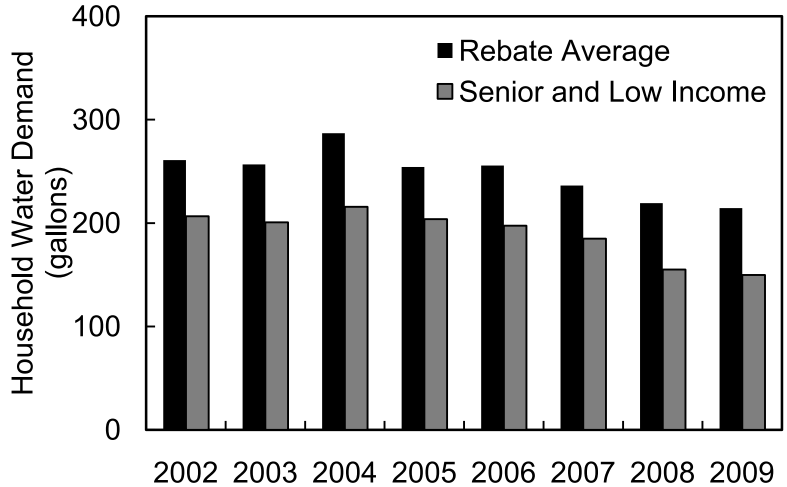

Figure 2.6 Comparison of household water demand in rebate (include SH, HEW and HEW) and SLIFR program

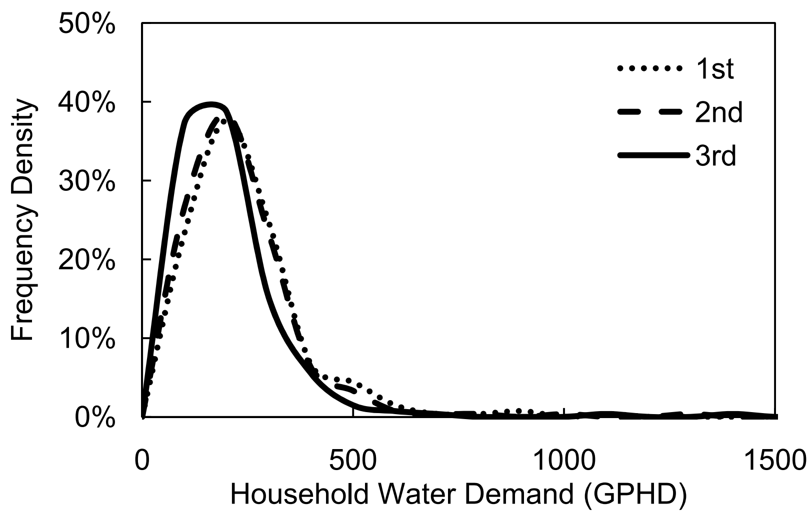

Figure 2.7 Frequency trend shifts in household water demand for senior and low income full retrofit customers

2.4 Conclusions

Statistically significant changes in water demand were observed for SH, HET, HEW and SLIFR program participants. The residential water demand for all rebate program participants shifted to lower demand levels over time. It was observed household water demand significantly decreased in the first two years after implementation, and there were still continuously effects in the third or fourth year of implementation.

The analyses indicated that high efficiency toilets and cloth washers had the highest potential in conserving water based on their observed water savings. The customers who had more than one type of water efficiency appliance experienced high water savings. These two conclusions are important to water demand management. The results indicate that people are becoming more aware of benefits of conserving water.

CHAPTER III

GOAL BASED WATER CONSERVATION PROJECTIONS BASED ON HISTORICAL WATER USE DATA AND TRENDS IN MIAMI-DADE COUNTY

(Mengshan Lee, Berrin Tansel, Maribel Balbin,

Sustainable Cities and Society, 2011, 1(2) pp 97-103)

3.1 Introduction

Demand side management of water resources has been recommended to be more suitable and effective for managing the imbalance between supply and demand than water resources reinforcement (Green, 2003; Inman and Jeffrey, 2006). Residential water demand, affected by economic, social and environmental factors, are expected to undergo substantial changes in the near (Schleich and Hillenbrand, 2009). Water demand projection is essential for water policy makers in planning urban development. They usually face difficulties to determine the future trends of water demand in the community. The water demand projection can be addressed from price (Arbués et al., 2010; Rosenberg, 2010), time, spatial and weather (Gato et al., 2007) perspectives, and only little researches have done studies in consideration of water use efficiency technologies (i.e. best management practices, BMPs). (Hern et al., 2008; Mayer et al., 2004)

Developments and implementations of water conservation BMPs target to ensure lower future water demand can be achieved. In recent years, BMPs have been widely adopted in developed countries and regions. Successful water conservation cases through implementations of BMPs have been reported in the USA (i.e. Seattle, San Francisco, Austin and Tampa; Hern, et al., 2008, Mayer, et al., 2004) and Australia (Sydney and Gold Coast; Turner et al., 2004, Willis et al. 2010). The BMPs participants are expected to have more than 35 percent of indoor water savings from replacement of high efficiency appliances (showerhead, faucet, aerator, toilet and cloth washer). Among all of the appliances, toilet and cloth washer are recommended to have the greatest potential in conserving indoor water use (Inman & Jeffery, 2006). Turner et al. (2004) also concluded that targeting participants to low income groups could be beneficial since they can provide high relative water savings. (Turner et al., 2004; Willis et al., 2010)

With the pressure of population growth, the stress on environmental resources and the demands for water in Miami-Dade County have increased. The Miami-Dade Water and Sewer Department (MDWASD) initiated a series of programs to promote water conservation by implementing best management practices (BMPs) (Balbin et al., 2010; Lee et al., 2011a; Pathakamuri et al., 2010). The BMPs initiated by MDWASD (2006) have been developed based on the efficiency measures, implementation techniques, schedule of implementation, scope, potential water savings, cost effectiveness, and references to assist end-users in implementation.

This study aims to understand the effects of BMPs on the changes in water demand in Miami-Dade County through 2030 by using three types of water conservation strategies: decrease in total water demand with conservation rate, decrease in daily water demand, targeted per capita water use. Water conservation rate, water savings and percentage of customers participating in BMPs will be also discussed. The main objectives of this study are to project the future water demand from demand side management point of view, and to understand the corresponding water demand changes from implementation of BMPs. This study will be of interest to water conservation professionals, development planning agencies, policy makers and researchers. The historical data collected in this study can also provide necessary baseline information for future water demand management studies.

3.2 Methodology

3.2.1 Goal Based Water Savings

Goal based water savings can be accomplished by different approaches: decrease in water demand with conservation rate, decrease in daily water demand, per capita water use oriented. Best management practice decision algorithm is presented in Figure 3.1. This algorithm illustrates the different strategies of water saving goals by BMPs to project the water use in 2030 using initial base year of 2008. By applying all of the BMPs in a household, the conservative water savings rate is equal to approximately 92.3 gallons per day or 33,690 gallons per year as shown in Table 3.1. The water savings is the difference between water use in initial fiscal year and target fiscal year after applying different kinds of conservation strategies. Also, the number of customers needed to be participating in BMPs can be obtained from water savings divided by the conservative water saving rate of BMPs (92.3 gallons per day). Figure 3.2 presents the sequential process for calculating desired water demand or per capita water use. The projected water demand is the estimated water demand deducts water savings with conservation strategies. By doing so, both desired water demand and water savings at present year can be calculated.

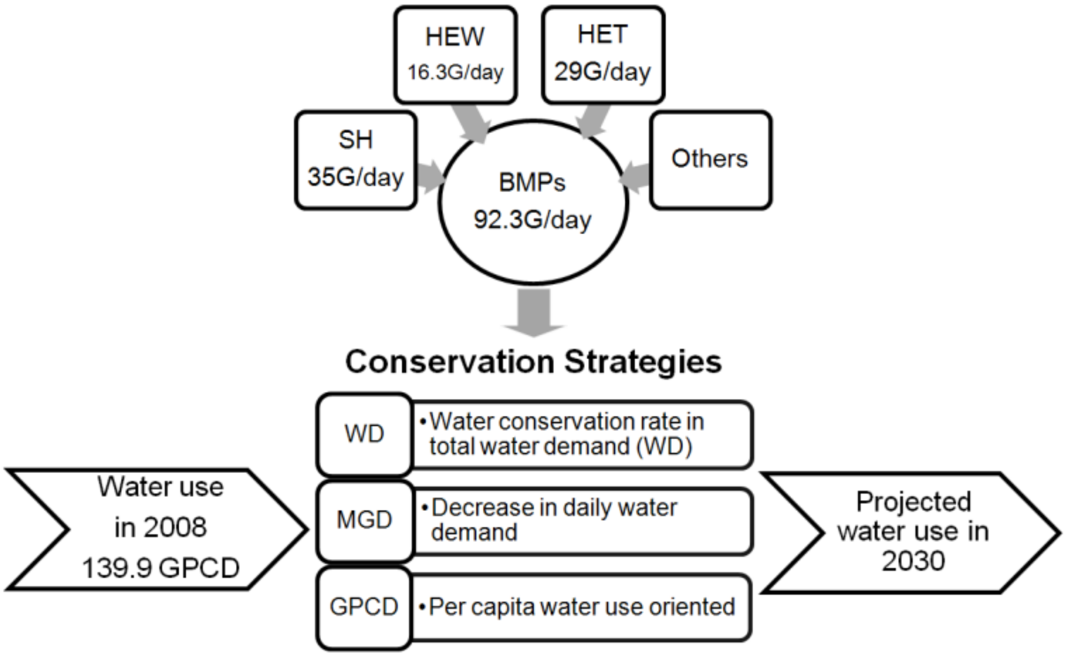

Figure 3.1 Best management practice decision algorithm

Figure 3.2 Sequential process in calculating desired water demand or per capita water use

Table 3.1 Estimated annual water savings by BMPs

BMP	Water use rate (GPMD[a])	Water savings (gals/year)
Toilet	29.0	10,585
Showerhead	35.0	12,775
Showerhead kit	12.0	4,380
Washer	16.3	5,950
Total	92.3	33,690

[a] GPMD: gallons per measurement per day

3.2.2 Estimated Water Savings by BMPs

As shown in Table 3.1, the water saving rates for toilet, showerhead, showerhead kit and washer are 29.0, 35.0, 12.0 and 16.3 gallons per measure per day, respectively. Assuming each single family residence has installed all of the BMPs; and considering only one measurement for each day; the total water savings could be 92.3 gallons per day or 33,690 gallons per year for one single family/customer. This is a very conservative estimate since typical use of these units would be more than one measure (i.e., one use) per day. The annual water savings by BMPs is denoted as $WS_{BMPs.}$

3.2.3 Population and Number of Customers Projections

Population data before 2000 were collected from US Census Bureau (2009). Since the population tends to have a steady growth after 2000, it was projected by increase rate about 1% per year. Population in this study is expressed as P_n in present (n=n) year or previous (n=n-1) year.

Number of customers is defined as the number of households in Miami-Dade County. Since number of customers is only available for retail customers, the total number of customers was corrected by water use ratio with wholesale customers. The total number of customer (TC) was calculated from the average water use ratio of retail (WU_R) and wholesale (WU_W) customers for 5 years from the equation 3.1 to 3.3 below:

$$R_{W/R} = \frac{\overline{WU_W}}{WU_R} \tag{3.1}$$

$$C_W = C_R \times (1 + R_{W/R}) \tag{3.2}$$

$$TC = C_R + C_W \tag{3.3}$$

where, $R_{W/R}$ is water use ratio of wholesale to retail customers (0.38 from 2004 to 2008); WU_W is water use of wholesale customers (million gallons); WU_R is water use of retail customers (million gallons); C_W is number of wholesale customers; C_R is number of retail customers; and, TC is total number of customers.

3.2.4 Terminology

Water demand (WD_n) was defined as summation of water sold for retail and wholesale customers and non-accounted water use. It is also related to the size of population, which means it could be also computed as population multiply by per capita use (PW_n). Hence, water demand could be expressed by the following equation:

$$WD_n \text{ (million gallons, MG)} = P_n \times PW_n \text{ (GPCD)} \times 365 \text{ days} \tag{3.4}$$

Percent change in water use was determined by difference in water use between the present year and the previous year. It could be calculated from the water demand in present year (WD_n) and the previous year (WD_{n-1}) as shown in equation 3.5:

$$C\,\% = \frac{WD_{n-1}-WD_n}{WD_{n-1}} \times 100\% \tag{3.5}$$

Determination of conservation rate is essential for obtaining degree of water conservation. Assuming the water conservation trend follows a first order model, the water demand in target year (2030) can be estimated from the water demand in the base year (2008) as follows:

$$X = X_0 e^{-RT} \tag{3.6}$$

where, X is water demand (MG) or per capita water use (GPCD) in target year; X_0 is water demand (MG) or per capita water use (GPCD) in base year; R is water conservation rate (%); and, T is time in years.

Water Savings is most related to difference of water demand within two continuously year. Since the water demand changes over time, the total water savings (TWS) was estimated by equation 3.7, where PW is the per capita water use (GPCD):

$$\text{TWS (MG)} = \sum_{n=2009}^{n=2030} P_n\,(PW_{n-1} - PW_n) \times 365 \tag{3.7}$$

Number of customers participating determines the efforts for water conservation practices. Percentage of customer participating BMPs (PC_{BMPs}) was correlated to number of customers participating (C_{BMPs}) to total number of customers (TC) as shown in equation 3.8 and 3.9:

$$C_{BMPs} = \frac{\text{TWS (MG)}}{WS_{BMPs}\text{ (33,690 G/customer)}} \tag{3.8}$$

$$PC_{BMPs} = \frac{C_{BMPs}}{TC} \times 100\% \tag{3.9}$$

3.3 Results

3.3.1 Projection of Population and Total Number of Customers

Projections of population and total number of customers through 2030 are presented in Figure 3.3 (a) and 3.3 (b), respectively. Population is increasing with a steady rate of 1% per year. The projected number of customers was calculated by the assuming 0.39% increase per year which is the increase in customers from 2007 to 2008. It is projected that the total number of customers would increase from about 577,000 in 2008 to 628,000 in 2030. And the population might rise from 2.2 to 2.8 millions.

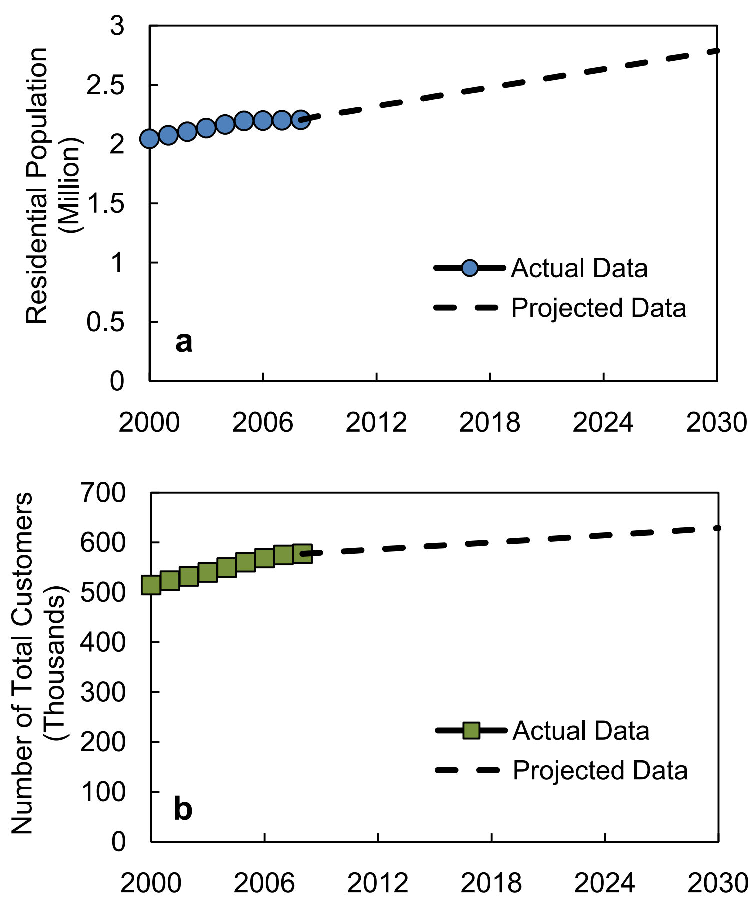

Figure3.3 Projection of (a) residential population (b) total number of customers

3.3.2 Results of Goal Based Projections

3.3.2.1 Scenario I: Targeting a Defined Water Conservation Rate

A series of goal based water savings projections were performed to achieve a specific annual water conservation rate (as % reduction in water demand) using 2008 as the base year for total water demand (wholesale, retail and non-account). The projected water demand was obtained from the estimated water demand from the previous year multiplied by appropriate water conservation rate. For defined annual conservation rates (R) ranging from 0.25% to 2%, projected water demand were calculated as follows:

$$WD_p = WD_E \times (1\text{-}R)\% = P_n \times PW_{n-1} \times 365 \text{ days} \times (1\text{-}R)\% \qquad (3.10)$$

where, WD_p is projected water demand (MG); WD_E is estimated water demand (MG); R is Annual water conservation rate (%).

Changes in daily water demand and per capita water use with percent decreased in water demand are illustrated in Figure 3.4 and 3.5, respectively. Solid rhombus lines reveal the projection data planned by MDWASD in 2009. Other lines display their trends through 2030 at various water conservation rates. With the conservation rate less than 1%, the daily water demand increases constantly with year, on the contrary, while the rate greater than 1%, the daily water demand decreases with year. From the water supply point of view, since population is growing with year, the water demand should either increase or stay almost the same level. Also as shown in Figure 3.5, the per capita water use is near 90 GPCD in 2030 with 2% conservation rate, which has a huge difference comparing to the use of 139.9 GPCD in 2008.

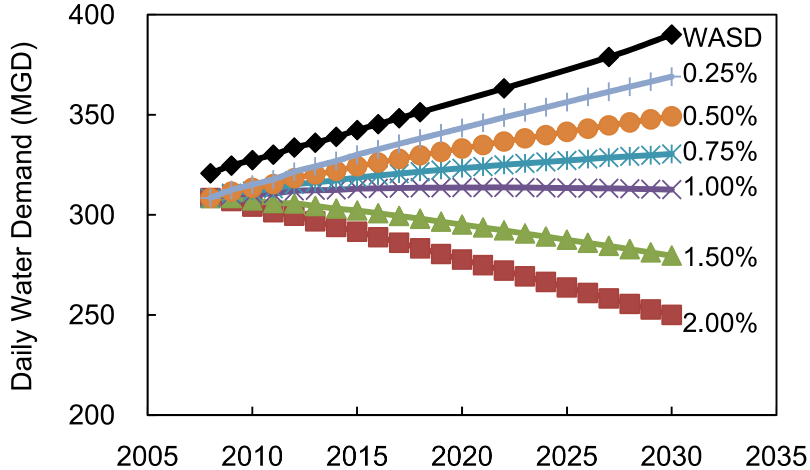

Figure 3.4 Change in daily water demand with various percent decreases in water use

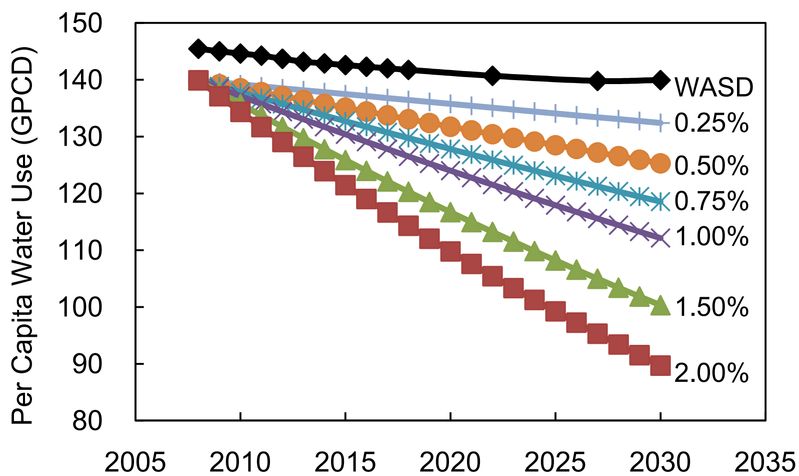

Figure 3.5 Change in per capita water use with various percent decreases in water use

Detailed information of estimated water use, projected water use, water savings, projected water demand, projected per capita water use, projected number and percentage of customers to participate in BMPs with water conservation goal from 0.25 to 2% are provided in Table 3.2. The total number of customers was projected as described in methodology section. Based on the information presented in Table 3.1, the annual water saving for a single family (one customer) is 33,690 gallons. By using the correlation between the customers and the annual water savings, to achieve a 0.5 to 2% water conservation rate each year, the percentage of customers needed to join the BMPs are provided in the last row in each category, which is estimated at between 1.5 and 11.7 % per year. Last column in Table 3.2 also includes the total water savings and total percent of customers participating. With water conservation rates of 0.25%, 0.5%, 0.75%, 1.0%, and 2%, total amounts of water savings were estimated at 6.9, 13.4, 19.5, 25.4 and 45.7 billion gallons for the 22 years period (2009-2030), respectively. It is obviously that the percentage of customers will exceed 100% if the conservation rate is greater than 0.75%.

3.3.2.2 Scenario II: Targeting a Defined Decrease in Daily Water Demand

The decrease in daily water demand approach is using the same process as described in methodology section and it is similar to the decrease with water conservation rate approach. The per capita water use in 2030 is 135.5, 131.1, 122.3 and 116.7 GPCD while the decrease in daily water demand is 0.5, 1.0, 2.0, 2.64 MGD (Table 3.3). The water savings to be achieved by 100% of customers participating in BMPs, the maximum amount of water saved by BMPs would be about 2.64 MGD from 2009 to 2030. Based on the conservation rate and percentage of customers participating, the appropriate

Table 3.2 Detailed water conservation information in decreasing of water use

% Decrease	Year	2008	2009	2010	2011	2015	2020	2025	2030	Average
	Estimated water use (MG)	112,579	114,316	113,274	112,228	108,609	103,419	98,235	93,125	
	Total number of customers (unit)		579,447	581,707	583,976	593,139	604,796	616,682	628,801	
2.00%	Projected water use (MG)		112,030	111,008	109,983	106,436	101,350	96,270	91,262	
	Water savings (MG)		2,286	2,265	2,245	2,172	2,068	1,965	1,862	2,077
	Projected water demand (MGD)	308.4	306.9	304.1	301.3	291.6	277.7	263.8	250.0	
	Percent of customers participating (%)		11.7	11.6	11.4	10.9	10.2	9.5	8.8	10.2
1.00%	Projected water use (MG)		113,173	113,285	113,385	114,276	114,481	114,405	114,102	
	Water savings (MG)		1,143	1,144	1,145	1,154	1,156	1,156	1,153	1,153
	Projected water demand (MGD)	308.4	310.1	310.4	310.6	313.1	313.6	313.4	312.6	
	Percent of customers participating (%)		5.9	5.8	5.8	5.8	5.7	5.6	5.4	5.7
0.75%	Projected water use (MG)		113,458	113,858	114,246	116,311	117,999	119,417	120,612	
	Water savings (MG)		857	860	863	879	892	902	911	888
	Projected water demand (MGD)	308.4	310.8	311.9	313.0	318.7	323.3	327.2	330.4	
	Percent of customers participating (%)		4.4	4.4	4.4	4.4	4.4	4.3	4.3	4.4
0.5%	Projected water use (MG)		113,744	114,433	115,111	118,378	121,616	124,635	127,475	
	Water savings (MG)		572	575	578	595	611	626	641	608
	Projected water demand (MGD)	308.4	311.6	313.5	315.4	324.3	333.2	341.5	349.2	
	Percent of customers participating (%)		2.9	2.9	2.9	3.0	3.0	3.0	3.0	3.0
0.25%	Projected water use (MG)		114,030	115,008	115,981	120,475	125,334	130,067	134,711	
	Water savings (MG)		286	288	291	302	314	326	338	312
	Projected water demand (MGD)	308.4	312.4	315.1	317.8	330.1	343.4	356.3	369.1	
	Percent of customers participating (%)		1.5	1.5	1.5	1.5	1.5	1.6	1.6	1.5

Table 3.3 Comparison of water savings in decrease amounts in daily water demand

Conservation rate (MGD)	2.64	2.0	1.0	0.5
Water savings from 2009-2030 (BG)	21.2	16.1	8.0	4.0
Number of customers have to participating (thousands)	628.8	476.7	238.3	119.2
Total number of customers in 2030 (thousands)	628.8	628.8	628.8	628.8
Percentage of customers participating in 2030 (%)	100.0	75.8	37.9	18.9
Per capita water use in 2030 (GPCD)	116.7	122.3	131.1	135.5

*MGD = million gallons per day

conservation rate could be targeted between 1 to 2 MGD through 2030. With approved conservation rate of 2 MGD, it is projected that the per capita water use could be reduced to 122 GPCD in 2030.

3.3.2.3 Scenario III: Targeting a Defined Reduction in Per Capita Water Use

For this approach, the target per capita water use in 2030 was set to values ranging from 70 to 130 GPCD. Table 5 reports the annual water conservation rates, water use and water savings corresponding to specific per capita water use rates in 2030. The water conservation rate could calculated from equation 6 ranged from 0.33 to 3.15% per year. The total water savings calculated from equation 3.7 ranged from 9 to 64 billion gallons (BG) from 2009 to 2030. Figure 3.6 displays the relationship between per capita water use and total water savings, with in target per capita water use from 70 to 130 GPCD. This relationship could be expressed as follows:

$$y = -0.9159\,x + 128.19 \quad \text{and } R^2 = 1 \tag{3.11}$$

where, y is the total water savings and x is the target per capita water use in 2030.

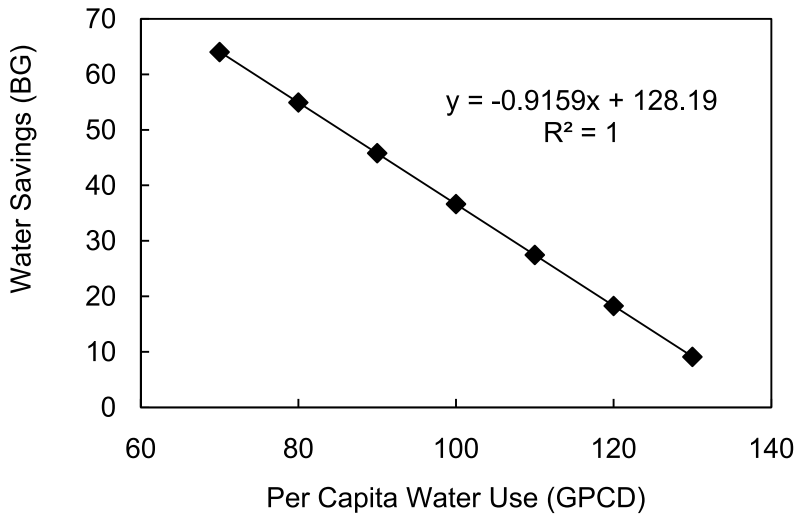

Figure 3.6 Relationship between total water savings and per capita water use

Table 3.4 Comparison of water conservation rate, total water needed and annual water savings at different per capita water use scenarios in 2030.

Desired per capita water use (GPCD)	139.9[a]	130	120	110	100	90	80	70
Daily water demand in 2030 (MGD)[b]	388	362	334	306	278	250	210	193
Total water savings (BG) from 2008 to 2030[c]	N/A	9.1	18.3	27.5	36.6	45.8	54.9	64.0
Water conservation rate (%)[d]	0.0	0.3	0.7	1.1	1.5	2.0	2.5	3.2

[a]: 139.9 GPCD is the per capita water use in 2008.
[b]: water demand = target per capita water use ×population in 2030.
[c]: total water savings is obtained from formula 3.7.
[d]: water conservation rate is calculated from formula 3.6.

3.4 Discussions

With a steady growth in population, it is challenging to expect a decrease in total water demand. Therefore, it is anticipated that water conservation rate greater than 1% is over and above MDWASD current stage (see Figure 3.4), and the 2% conservation rate is relative hard to achieve (Figure 3.5). This indicates that other water conservation approaches need to be investigated to achieve additional water savings (i.e., 1% more). Other than promoting water conservation practices to residential customers, delivering the practices to water-intense industries (i.e., hotel and restaurants) can be targeted to decrease total water demand. Targeting water conservation to hotel and restaurants may contribute to a significant amount of water savings since economy in the greater Miami area has been based on tourism.

In the scenario of decrease in target daily water demand, it is evinced that the appropriate rate should be 1 to 2 MGD. The water savings (for all BMPs) in current stage for Miami-Dade County ranges from 1.2 to 2.3 MGD, and the savings is expected to increase in the future by introducing more practices and participants into the community. The slope (-0.9159) found in Equation (3.11) indicates that by reducing 1 GPCD of water use for the whole community can provide about 0.9 BG of water savings. This suggests that any committed efforts of conserving water can eventually endow a significant amount of water savings.

3.5 Conclusions

Based on the analysis, the most sensible goal based water conservation approach is setting water conservation rate to a specific daily water demand (Scenario II). This approach is reasonable and achievable based on the current water saving stage (with number of participants in BMPs) in Miami-Dade County. In order to reach the water savings goal of 2 MGD, approximately 76% of residential customers should be introduced to BMPs programs from 2009 to 2030. This number is rather high and it may be difficult to maintain a 2 MGD savings consistently over time, if only residential customers are considered. There were around 44,671 residential customers who benefited from the BMPs programs (i.e., Senior and low income full retrofit, SH, HET or HEW rebate programs) from October 2006 to June 2009, which is about 2.5% of the total customers per year and providing water savings ranges from 1.2 to 2.3 MGD. The number of customers participating in BMPs program is continuously climbing these years. Other water conservation practices such as increase water circulation cycle in cooling towers and sprinklers with soil moisture meter are expected to provide additional water savings. Also, expanding water conservation practices to water-intense industries can be beneficial in conserving water.

The US EPA water sense program (1998) defined a 70 GPCD standard for a single resident who has good sense of conserving water. After applying BMPs at 2 MGD water savings rate, it can be expected that the water use can be reduced to approximately 122.3 GPCD, which is still very different from US EPA's "water sense" conservation criteria. This also suggests that other water conservation strategies or tips should be investigated in order to achieve desired water savings. It can be foreseen that novel technologies in water efficiency will lead the market in the near future.

The water conservation plan in Miami-Dade County has made significant impacts on customers to live green (in terms of conserve more water and saving more energy) in South Florida. In addition, the tips on water conservation, wastes reduction, energy savings, and more efficient use of household alternatives are provided. The impact of these efforts are evinced by the water consumption data of the customers participating in water conservation programs as well as the water use records in Miami-Dade County who have made changes in their water use.

CHAPTER IV

INTEGRATED RESIDENTIAL WATER DEMAND MODEL INCORPORATING WATER CONSERVATION PRACTICES

(Mengshan Lee, Berrin Tansel, submitted to *Land Use Policy*)

4.1 Introduction

Residential water demand is affected by economic, social and environmental factors (Schleich and Hillenbrand, 2009). Policy makers and water utility managers often encounter difficulties in finding adequate information to determine future water demands in view of changing dynamics of a community. The effects of different types of tariffs on demand functions have been evaluated by consideration of price-elasticities (Arbués et al., 2003; Olmstead et al., 2007; Olmstead and Stavins, 2009) and property characteristics (Bradley, 2004; Fox et al., 2009; Jorgensen et al., 2009; Troy and Holloway, 2004). Variables that have commonly been considered in water demand models include household income, weather characteristics, composition of residence and use purpose (Arbués et al., 2003; Carter and Milon, 2005; Jorgensen et al., 2009; Kenney et al., 2008; Renwick and Archibald, 1998; Strand and Walker, 2005). Education level has also been reported to have a positive impact on water conservation (Hurd, 2006).

Water demand estimation can be challenging for new developments after policy changes which require rapid adjustments to implement water conservation practices (Lienert et al., 2005). New developments, including environmental improvements, can impact the demand profiles (Lundie et al., 2004). Recently, some major metropolitan areas have proposed water conservation practices such as water use restrictions, high-efficiency appliance rebates/exchange and water saving initiatives (Balbin et al., 2010;

Davis, 2008; Lee et al., 2011a). Thus, it is necessary to include water conservation practices in demand projections. However, availability of detailed and well controlled water use data has been a limiting factor for quantifying the effects of water conservation practices.

Renwick and Archibald (1998) first considered water conservation technologies in a water demand model. The results suggest that the reduction in water demand and distribution of water savings among household classes depend both on the policy instrument (water use efficient technologies) and the composition of aggregate demand. Renwick and Green (2000) indicated that mandatory policies were more significant in water savings (greater than 15% of reduction in demand), while voluntary policy instruments (i.e., use of water efficiency fixtures) could only contribute about 5-15% of reduction in water demand. A rebound effect of using water efficiency instruments was discussed by Campbell et al. (2004): water demand declining by regulating installation of low-flow fixtures and devices (3.5% reduction) but inclining by giving free retrofit device kits (3.8-4.6%). Table 4.1 compares the linear regression water demand models which incorporate water conservation practices and the corresponding estimated coefficients (positive or negative) that are correlated to water demand for each practice. Dummy variables were used for each water conservation practice for all listed models.

Since sufficient data for individual households are often not available, most studies use aggregated data at the community level (Gaudin, 2006; Schefter and David, 1985). The use of aggregate data can provide explanations for significant parameters in water demand estimation; however, using averages from aggregated data sets cannot provide an adequate understanding of the water use profiles in relation to household characteristics within the community. Incorporation of water conservation practices into water demand models often involve dummy variables to denote presence of the water conservation practices. Also, quantitative information related to different types of water conservation practices within the households is often overlooked. The characterization of water conservation practices is essential for accurate estimation since the nature of the measurements may vary either over time or cross-sectionally (Renwick and Green, 2000). There is an increasing amount of research on estimation of water demand at the micro level. Hence, methods which incorporate detailed household level data are still the preferred approach for estimation of water demand (Arbues et al., 2010; Hewitt and Hanemann, 1995).

This study proposes an improved residential water demand model using empirical panel data analysis approach. The model is calibrated using detailed and quantified household level data from a study group. The study group includes senior and low income single-families whose residences were retrofitted with high efficiency appliances. The model incorporate parameters such as property characteristics, household composition, weather conditions and water conservation practices (i.e., use of high efficiency appliances). Significances of the variables are compared to identify the key contributing factors on water demand changes.

Table 4.1 Comparison of water demand models which incorporate water conservation practices

Research	Water conservation practices	Coefficient
Renwick and Archibald, 1998	adoption of low flow toilets	−1.250
	adoption of low flow showerheads	−0.800
	adoption of water efficient irrigation technologies	−1.760
	landscape irrigation use restrictions	−6.600
Renwick and Green, 2000	low-flow toilet rebates	−0.004
	free plumbing retrofit kits	−0.090
	restrictions on certain types of water uses	−0.340
Campbell et al., 2004	low-flow fixtures and devices ordinance−phase I	+0.005
	low-flow fixtures and devices ordinance−phase II	−0.039
	low-flow fixtures and devices ordinance−phase III	−0.001
	water waste ordinance	+0.029
	retrofit device drop-off (free give away)	+0.038
	depot plumbing product pick-up (free give away)	+0.046
Domene and Sauri, 2006	consumer behavior index (number of adopted water-efficiency appliances)	−4.600

4.2 Methodology

4.2.1 Data Acquisition

Data sets used in this study were obtained from the public records of Miami-Dade County (MDC), Florida, USA. Before 2001, the county's per capita water use was over 160 gallons per capita per day (GPCD). After 2001, the per capita water use showed some fluctuations and a significant reduction to 140 GPCD in 2007. One of the reasons for this reduction may be the water conservation incentives promoted by Miami-Dade Water and Sewer Department (MDWASD) starting 2006 (Balbin et al., 2010; Lee et al., 2011b)

The study group used in this study included the MDC residents who participated the Senior and Low Income Full High Efficiency Fixture Retrofit Project promoted by

MDWASD. Selected project participants considered low income or seniors based on their property tax exemption data. The single-family residents selected were retrofitted (free of charge) with maximum two high-efficiency toilets, and maximum two high-efficiency shower heads which were equipped with shower head kits and aerators. The water use rating of the high efficiency appliances in comparison to traditional ones are displayed in Table 3.1. The expected water savings for high-efficiency shower head kit and toilet are 35 and 29 gallons per measurement (use) per day (GPMD), respectively.

The project was initiated in late 2006 and has been continuing. For this study, only the 271 participants who joined the program in the first year were considered. The data used in the analyses include these customers from October 1, 2006 through December 31, 2009. Water demand data (gallons per household per day, GPHD) for each participant are reported on a calendar year basis.

4.2.2 Selection of Model Variables

Variables considered in this study were classified into two major categories as dependent variable and independent variables. All the statistical analysis results were carried out using SAS 9.2 statistical software (SAS Institute Inc., North Carolina, USA).

4.2.2.1 Dependent Variable

The dependent variable was defined as the average water demand. Average water demand is usually expressed either per household usage (GPHD) or per capita water usage (GPCD). The per capita water usage is calculated as the ratio of total amount of water demand to the total number of occupants in the unit. Residents with zero water consumption imply unoccupied residences and were not included in the analysis.

Household composition data were obtained from the MDC public records. Water consumption data were obtained from the water use records.

4.2.2.2 Independent Variables

Independent variables were selected based on potential significance and availability of data from public records. The variables included household characteristics (i.e., adjusted house size, lot size, building age, building type, number of rooms and property value as in 2009), household composition (i.e., number of occupants) and number of high-efficiency appliances (i.e., number and type). The data on household characteristics were available from the Office of The Property Appraiser in MDC (2010). Household characteristics such as size, age and market value were assumed to be correlated with the household income. Also, property values (i.e., assessed and market value) were assumed to be proportional to income level (Dandy et al., 1997).

The average annual temperature (T) and number of rainy days (RD) in wet season were also considered as independent variables. The wet season in Florida is from May to October which includes months with warm temperatures and significant rainfall. The number of rainy days was defined as number of days with cumulative precipitation that is equal or greater than 0.01 inch. The number of rainy days has been reported to be a better explanatory variable than the amount of precipitation in a given period (Martinez-Espineira, 2007). The temperature and rain activity data were obtained from the United States Historical Climatology Network (Menne et al., 2009).

4.3 Water Demand Model

A simple Ordinary Least Squares (OLS) equation is developed for estimating the water demand in relation to independent variables. The water demand model is composed of two major components: 1. water conservation practice adoption equations; and 2. water demand equation. The water conservation practice adoption equations include low flow shower heads (SH), low flow aerators (AE) and high-efficiency toilets (HET) as illustrated in Equations (4.1) to (4.3). The adoption equations are functions of the number of water conservation appliance (N_i) and the expected water savings (WS) per measurement (GPMD, Table 3.1) as shown below:

$$SH_i = N_{SH,i} \times WS_{,\,SH} \tag{4.1}$$

$$HET_i = N_{HET,i} \times WS_{,\,HET} \tag{4.2}$$

$$AE_i = N_{AE,i} \times WS_{,\,HEW} \tag{4.3}$$

where, i=1, 2, 3….., total number of participants

The water conservation practice adoption equations are then incorporated into the water demand model (Equation 4.4) as presented below. The model is calibrated with detailed household data. Definitions and descriptive statistics of the variables used in the model are listed in Table 4.2. Variables YR_j (j = 1 to 4) are dummy variables corresponding to each year with implementation of water conservation practices. The water demand (WD) model can be written as follows:

$$\begin{aligned} WD = f\,(&AF, LS, BA, PP, BED, BATH, FL, MV, AV, T, RD, \\ &SH, HET, AE, YR_1, YR_2, YR_3, YR_4) \end{aligned} \tag{4.5}$$

Table 4.2 Descriptive statistics for dependent and independent variables (n=271)

Variable	Description	Unit	Mean	SD[a]	Min	Max
WD	Water demand per household	Gal/Day	171.7	138.4	8.0	1635
AF	Adjusted square footage	1000 ft^2	1.4	0.4	0.4	3.2
LS	Property lot size	1000 ft^2	7.6	7.0	2.1	111.6
BA	Building age	Years	63.2	16.4	15.0	98.0
FL	Number of floors	Floors	1.0	0.2	1.0	2.0
MV	Property market value (2009)	$1000	196.5	85.0	65.9	693.2
AV	Property assessed value (2009)	$1000	96.6	53.1	27.1	385.1
PP	Number of occupants	People	2.3	1.2	1.0	6.0
BED	Number of bedrooms	Number	2.7	0.7	1.0	5.0
BATH	Number of bathrooms	Number	1.5	0.5	1.0	3.0
T	Average temperature	Degree F	77.7	0.3	77.2	77.9
RD	Rainy days in wet season[b]	Days	95.3	7.4	86.0	103.0
SH	Adoption of H.E. shower head[c]	Number	1.4	0.5	1.0	2.0
HET	Adoption of H.E. toilet[c]	Number	1.5	0.5	1.0	2.0
AE	Adoption of H.E. aerator[c]	Number	2.0	0.7	1.0	3.0

[a] SD: standard deviation
[b] from April to October
[c] H.E.: high efficiency

4.4 Results and Discussions

Historical water demand trends for the Senior and Low Income Full High Efficiency Fixture Retrofit Project participants from 2002 to 2009 are presented in Figure 4.1. The actual water demand data indicate that the participants in the program experienced significant reduction in water use, especially after 2006. Estimated coefficients for each determinants of the water demand model are listed in Table 4.3. The numbers in the parenthesis include standard errors of the estimated values. Contributions of each variable were calculated as the ratio of sum of squares for each variable to total sum of squares.

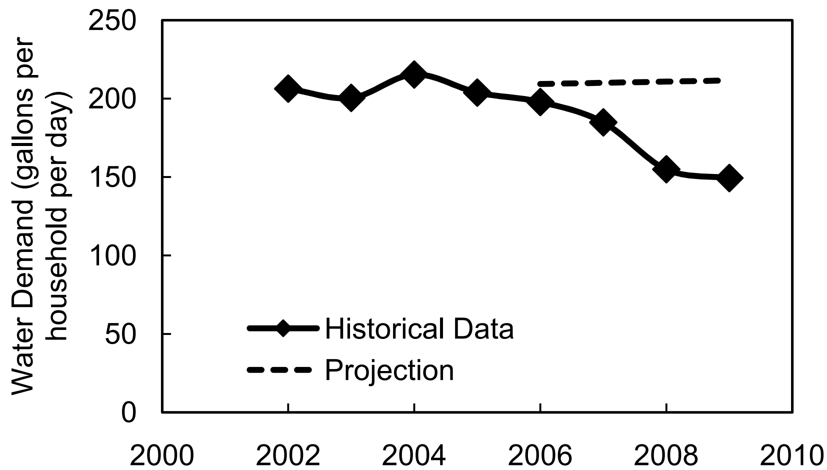

Figure 4.1 Time series of water demand for the project participants (n=271)

From the values of coefficients, lot size (LS), number of occupants (PP), number of bathrooms (BATH) and temperature (T) exhibited positive correlation with water demand. The variables which possessed a negative correlation with water demand included adjusted square footage (AF), building age (BA), number of floors (FL), property market value (MV), property assessed value (AV), number of bedrooms (BED), number of rainy days (RD), adoption of high-efficiency toilets (HET), shower heads (SH) and aerators (AE). Among these variables only adjusted square footage (AF), number of bathrooms (BATH) and adoption of high-efficiency aerators (AE) are significant at the 0.05 level.

The adjusted square footage could be misleading as one would expect higher water use with increasing living space. However, in MDC, the adjusted square footage is not only the living space but also includes other areas. In addition to the 100% of base living area (air conditioned space), the adjusted square footage used in this study measured from outside of the building that includes carport area, garage, open patios, roof overhang area, utility room, area in second story and additional area after original construction. These parts of the building are added into adjusted square footage at different fraction of their actual area. For instance, the footage includes 33% of carport area, 50% of garage, 33% of patio, 25-33% of roof overhang area, 50% of utility room and 80% of second floor area. A single family would have significantly higher adjusted square footage in comparison to a condominium when both of them have the same base living area. Therefore, complexities of adjusted square footage are expected in this study. As a result, a negative correlation was observed for this study group. The average house adjusted square footage for customers with full retrofits (i.e., 2 of HET, 2 of SH, and ≥ 2 of AERO) was 1876.3 ft^2, which is within the high square footage range. Therefore, the effects of high efficiency appliances may have overcame the effects of house size.

Climate variables are critical for seasonal water consumption (i.e., outdoor activities) (Gutzler and Nims, 2005). Rainfall causes temporary reduction in water demand, however, the effect becomes less significant over time (Miaou, 1990). Temperate was found to be positive correlated to water demand that water demand increases as temperature raises. The number of rainy days was observed to be negatively correlated with water demand and it was partially due to the water restriction policy in effect in South Florida during the wet season.

The regression analyses result indicated that with critical F(16,1068) value of 1.65 at 5% significance level, the model had adequate predictive capability (F=114.22). The adjusted R-square value was 0.63. R-square values are typically lower for complicated cross-sectional models with large observation population since each cross section contains specific characteristics that cannot be adequately modeled (Agthe and Billings, 2002). The three variables which were significant at 0.05 level accounted for about 63% of the estimated water use (adjusted square footage at 18.72%, number of bathrooms at 17.85%, and adoption of high efficiency aerators at 26.10%).

Table 4.3 Estimated coefficients for water demand model (standard error in parenthesis)

Variable	Description	Coefficient		Contribution (%)
Property characteristics				
AF	Adjusted square footage	−31.59	(14.88)[c]	18.72
LS	Lot size	0.66	(0.60)	4.98
BA	Building age	−0.36	(0.27)	7.73
FL	Number of floors	−30.23	(26.17)	5.54
MV	Market value	−0.11	(0.08)	7.98
AV	Assessed value	−0.03	(0.11)	0.25
Household composition				
PP	Number of occupants	1.84	(3.54)	1.13
BED	Number of bedrooms	−8.60	(7.00)	6.27
BATH	Number of bathrooms	25.48	(12.28)[c]	17.85
Weather variables				
T	Temperature	5.25	(2.53)[b]	N/A
RD	Rainy days in wet season	−1.05	(2.02)[b]	N/A
Adoption of water conservation practice				
HET	Adoption of H.E. toilet[a]	−0.32	(0.44)	2.24
SH	Adoption of H.E. showerhead[a]	−0.28	(0.52)	1.22
AE	Adoption of H.E. aerator[a]	−1.42	(0.57)[c]	26.10
Adjusted R^2		0.63		
F value		114.22		
p value		<0.001		

[a] H.E.: high efficiency
[b] biased estimate
[c] significant at 0.05

4.4.1 Effects of Household Characteristics

Household characteristics can have significant effects on water demand. However, the effects of the household characteristics is often uncertain since it is correlated with other factors (Schneider and Whitlatch, 1991). Adjusted square footage (AF) and building age (BA) were found to be negatively correlated with water demand. The water demand is expected to decrease with building age since new buildings are often equipped with several water-efficiency appliances such as cloth washer or dish washer and have relatively low leakage through the pipes. In this study, approximately 88% of the households were built before 1970. Adjusted square footage, market and assessed value (MV and AV) of the property, are often considered to be correlated with income or wealth level. This implies that affluent people may be more aware of the benefit of conserving water or water saving tips especially they have water-efficiency fixtures installed. This finding is different from the previous studies (Agthe and Billings, 2002; Hanak and Browne, 2006; Harlan et al., 2009; Nauges and Whittington, 2010; Vickers, 2001) which stated that wealthier households tended to use more water since they had more opportunities to purchase water-using appliances and they might value water savings less than poorer households.

A negative correlation was found between the water demand and number of floors (FL). Building type for the project participants are all single-family units with maximum two stories. The negative correlation suggests that low water demand usually occurs in flats and cluster homes (Fox et al., 2009). There was also a negative correlation between the water demand and number of bedrooms (BED). In this study, the additional bedrooms may be vacant since the study group included senior and low income customers.

Lot size (LS), number of occupants (PP) and number of bathrooms (BATH) are variables that were positively correlated with water demand. Presence of garden (lot) shows a significant positive effect on water demand since the water is used for gardening purposes (Fox et al., 2009; Harlan et al., 2009). This suggests that water restriction for outdoor activities, especially for lawn watering, may contribute to a significant amount of water savings. Outdoor water restrictions are considered to have more impacts on lawn watering than for garden beds watering (Randolph and Troy, 2008)

Household size (number of occupants, PP) and number of bathrooms (BATH) are directly correlated with water demand (Memon and Bulter, 2006). Distributions and corresponding average water demand (GPHD) for PP and BATH variables are presented in Table 4.4. Most of the households were anticipated to have less than three occupants (85%). The majority of the households had between 1 and 2 bathrooms since the study group only included single-family units in urban area with average adjusted square footage of 1400 ft^2 only (Table 4.2). Thus, water demand did not vary significantly with the number of occupants due to limitations of the study groups.

As shown in Figure 4.2, a significant positive effect of number of bathrooms on water demand was observed (trend line in solid and standard deviation lines in dash). The increase of number of bathrooms may offer more opportunities in using water. Despite the trend upwards with increase of bathrooms, there are few exceptions (high water consumption) found in one bathroom range. For instance, the one with highest water demand (approximately 1,100 gallons per day) has a lot size of 30,000 ft^2 (average lot

Table 4.4 Distribution of variable counts and their relationship with water demand

Variable	Count	Water demand (GPHD)[a]
Number of occupants (PP)		
1	72	168.0
2	106	168.0
3	51	181.0
4	29	196.0
5	8	93.6
6	6	190.2
Number of bathrooms (BATH*)*		
1	113	167.3
1.5	63	184.4
2	86	162.0
3	10	225.0

[a] gallons per household per day

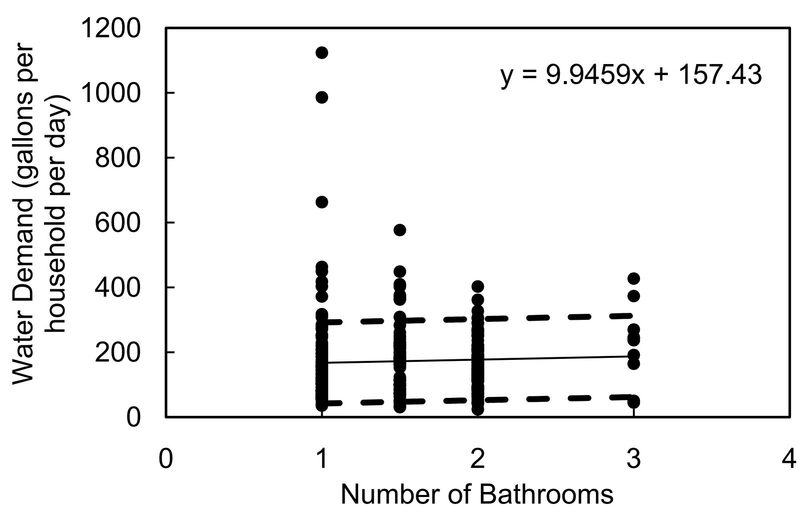

Figure 4.2 Correlation of total number of bathrooms to daily water demand (dashed lines indicate ± standard deviation)

size in this study is 7,600 ft^2), and the high water demand could be due to irrigation. This case implies that water demand can be significantly reduced by focusing attention to specific areas or households with high rates of consumption and by water conservation awareness programs (Inman and Jeffrey, 2006; Larson et al., 2009).

4.4.2 Effects of Water Conservation Practices

Estimated regression coefficients for water conservation practices (i.e., HET, SH and AR) show negative effects on water demand as presented in Table 4.3. Use of water efficiency appliances have been proposed and proven to effective measures for water savings (Anand and Apul, 2011; Lee et al., 2011a; Pathakamuri et al., 2010; Randolph and Troy, 2008). Millock and Nauges (2010) noted that environmental attitudes and ownership status are strong predictors of number of households who are willing to install water efficiency appliances.

Correlation of number of water efficiency appliances to daily water demand is displayed in Figure 4.3. The daily household water demand is positively correlated with the number of water conserving appliances for toilets and shower heads. For high efficiency aerators, the water demand shows a significant negative trend with increase number water saving appliances (Figure 4.4). In a study of water use distribution for twelve cities in the US, the highest indoor water consumption for residential single family homes was found to be toilets (27.6%), followed by clothes washers (21.7%), showers (16.8%), and faucets (13.7%) (Vickers, 2001). According to the findings, water use at the faucets may account for a higher percentage in the households in this study. (Millock and Nauges, 2010).

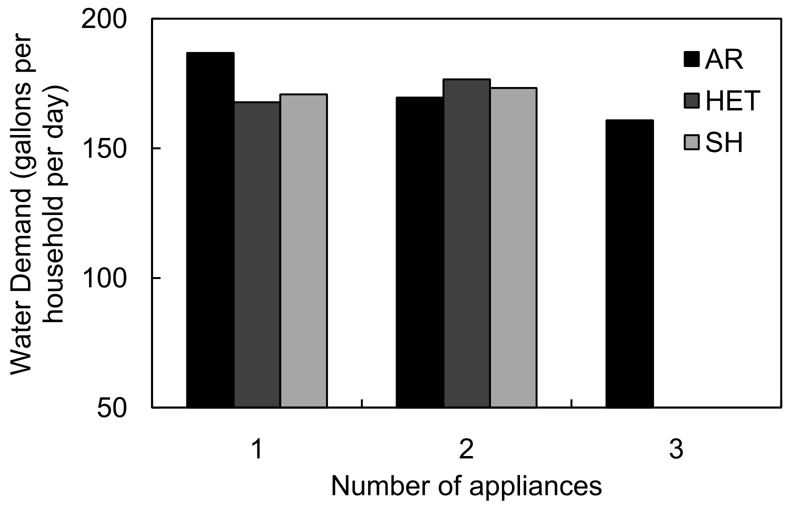

Figure 4.3 Effect of number of water conservation appliances to daily water demand

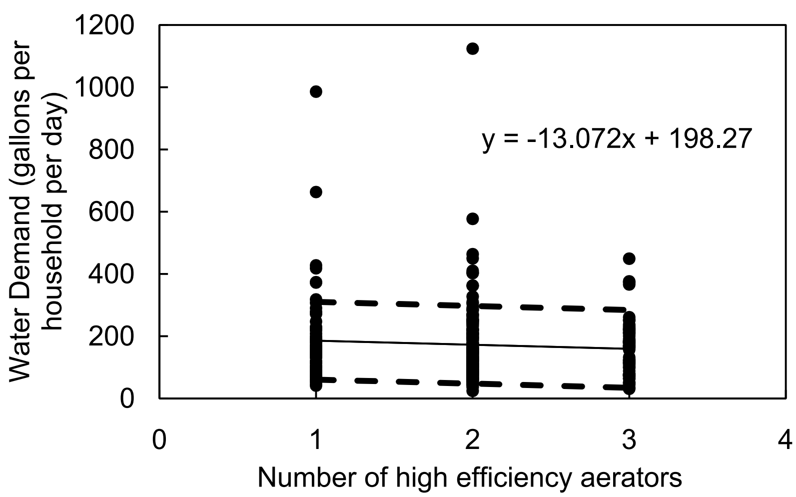

Figure 4.4 Correlation of number of high efficiency aerators to daily water demand (dashed lines indicate ± standard deviation)

Table 4.5 Estimated water reduction percentage for water conservation practices

Variable	Model coefficient	Variable mean	Change in demand (%)	
			This study	Previous study[a]
HET	−0.32	42.1	− 7.9	−10.0
SH	−0.28	32.1	− 5.1	− 8.0
AR	−1.42	23.8	−19.7	N.A.

[a] Renwick and Archibald, 1998

Water demand reduction (as percentage) for each water conservation practice is shown in Table 4.5. The water demand reduction was calculated as percent change in water demand using model coefficients (Table 4.2) and variable means (Table 4.3) (i.e., how much high efficiency appliances contribute to reduction in water demand). In this study, the reduction percentage was highest for AR (19.7%), followed by HET (7.9%) and SH (5.1%); which were in the same order reported in previous studies (10 to 11% for HET and 6 to 9.7% for SH) (Renwick and Archibald, 1998).

Income level has been reported to be a factor effecting times of shower and low income group usually have two showers less per week than that in high income group (Domene and Sauri, 2006). Showering behavior (showering or bathing) can also affect the impact of shower heads on water conservation. For example, if a customer chooses bathing over showering, the water use can be as much as twice of that for showering (Memon and Bulter, 2006). Also, offsetting behaviors such as awareness of water conservation but using more water could be observed for participants with high efficiency shower heads (Inman and Jeffrey, 2006). Water use for toilet flushing is correlated to the time spent in the house and number of users in the household. Small variation of household residents in this study can be the reason that water savings for shower head and toilets remained relatively stable.

Water use for faucet (with aerator) had the most significant effect on water demand reduction among all of the water conservation practices considered. Water uses for faucet include cleaning, rinsing and food preparation; and the uses are expected to be lower for customers who have an automatic dishwasher. The project participants (senior and low income) may consume more (or use more frequently) water from faucets because they are frugal in using dishwasher (consume both water and electricity). Therefore, the water savings in this study group are more significant on aerators.

4.5 Conclusions

Impacts of different determinants on water demand were analyzed using a household level model. The number of rainy days was observed to be negatively correlated with water demand. This can be due to the water restriction policy in effect in South Florida during the wet season. The adjusted square footage and number of bathrooms were found to be most significant parameters for water demand among the household characteristic determinants. Definition of adjusted square footage (which used for tax purposes) could be misleading. A negative correlation was observed between the adjusted square footage and water demand due to the limited size of the residential units considered in the study. There was a significant positive effect between the number of bathrooms on water demand. The increase of number of bathrooms may offer more opportunities in using water.

The adoption of water conservation practices was effective in conserving water. There was not sufficient evidence to conclude that the reduction in water savings were related to the quantity or type of water conservation practices adopted. However, the high efficiency aerators indicated the highest water saving potential. The water uses for different appliances were highly dependent on user characteristics and habits. Variations in household habits may be a factor that limited the performance of the appliances. The results of the water demand model can be useful for future management programs in reducing water demand.

CHAPTER V

RESIDENTIAL WATER CONSERVATION PRACTICES: LIFE CYCLE ASSESSMENT OF DEMANDS AND EMISSIONS

(Mengshan Lee, Berrin Tansel, submitted to Environmental Science and Technology)

5.1 Introduction

Sustainable water demand management and urban planning are critical issues from environmental, social and economic perspectives. Population growth, economic demands, climate and lifestyle changes could significantly increase the stress levels on water resources (Arnell et al., 2011; Mohamed, 2000; Postel et al., 1996). Hence, the environmentalists are pressuring water sectors towards implementing sustainable management practices (Wong and Brown, 2009). The water demand management concerns include not only increasing needs and limited availability of water resources but also greenhouse gas (GHG) emissions that are directly attributed to water system operations (Fidar et al., 2010).

Urban water systems, including supply, distribution, end-use and treatment, have significant impacts to the environment due to GHG emissions associated to energy consumption. Environmental impacts from residential water system are the most significant during end-use stage (i.e., water consumption), particularly for heating purposes (Fidar et al., 2010; Hackett and Gray, 2009; Reffold et al., 2008). A study of carbon emissions from water systems showed that water supply, distribution and treatment only accounted for approximately 11% of the total water-related carbon emissions and the remaining 89% is attributed to water end-use demand (Reffold et al., 2008).

Life cycle assessment (LCA) has been widely used as a tool for understanding and evaluating the potential environmental impacts of products or services. LCA is applied to quantify environmental impacts of a product during its life-cycle phases: raw material production, manufacturing and assembly, transport, end-use/demand and end-of-life disposal. A comprehensive LCA study typically includes four phases: 1. goal and scope definition (system boundary), 2. life cycle inventory analysis, 3. life cycle impact assessment, and 4. interpretation (Finnveden et al., 2009). The results of LCA can be helpful for promoting sustainable development and increasing environmental awareness in public (Racoviceanu et al., 2007).

A LCA model of integrated water supply and wastewater treatment system was first introduced by Lundie et al. (2004). LCA studies on water management (from supply, distribution and treatment prospective) have been well developed in recent years, and most of the studies have addressed the environmental impacts from individual process (Foley et al., 2010; Lundie et al., 2004; Lundin et al., 1999; Palme et al., 2005; Vince et al., 2008). However, there are only a few studies that have investigated the life cycle impacts of efficient technologies (Anand and Apul, 2011), especially for appliances with reduced water demands. Water efficiency conservation scenario is worthwhile for rendering sustainable water system (Racoviceanu and Karney, 2010) especially when technology and efficiency improvements of appliances may contribute to lower impacts from the production stage (Bole, 2006).

As part of the efforts to achieve sustainable urban development, water conservation practices have been widely adopted for demand management. Residential water conservation practices (i.e., installation of water efficiency appliances) can be beneficial from several aspects: 1. residential appliances have a major contribution on household water demand, and, 2. the potential water savings for efficient appliances could be significant (Balbin et al., 2010; Baumann et al., 1998; Fidar et al., 2010; Kenney et al., 2008; Lee et al., 2011b; Millock and Nauges, 2010; Olmstead and Stavins, 2009; Pathakamuri et al., 2010). Furthermore, water efficiency incentives (i.e., rebate or exchange programs) for household appliances are considered to be more acceptable by the public in comparison to other water management policies such as price increase or water restrictions (Millock and Nauges, 2010; Randolph and Troy, 2008).

One of the applications of LCA is to estimate the optimal lifespan of a product. Lifespan of an appliance can be determined by life-cycle costs, costs of conserved energy, and annualized net dollar savings (Young, 2008). Chalkley et al. (2003) proposed a method for estimating optimal lifespan to keep the environmental impacts of a product at a minimum. The method considers the environmental impacts of energy consumption from production and end-use stages of a product. The optimized lifespan of a product is important to reduce overall environmental impacts by regular replacement of old appliances while allowing new products to be designed with appropriate level of durability (Chalkley et al., 2003).

This study assesses the environmental impacts of household water demand related appliances such as clothes washer, toilet, and shower head (including standard and efficiency models) by considering energy consumption and associated GHG emissions through the LCA. The LCA analysis includes raw material production, manufacturing, end-use demand and end-of-life disposal. The study especially focuses on hidden usage and environmental impacts from end-use and demand phases (i.e., from water supply to wastewater treatment). An analysis of optimal lifespan of the appliance from energy consumption perspective was also conducted. The results can be of interest for design of water systems and urban planning for sustainable development.

5.2 Methodology

5.2.1 System Boundary

The LCA analysis included raw material production, manufacturing, end-use demand and end-of-life disposal stages. Hence, for the LCA, the system boundary was defined as presented in Figure 5.1. Operations or processes that contribute to the life cycle of water-using appliances fall within the system boundaries. Transportations between different stages were considered negligible.

Different from other studies that only considered general LCA stages; this study includes three water-related processes (water supply, wastewater treatment and water heating) for a comprehensive analysis of the life cycle of water conservation appliances. The hidden energy use and associated GHG emissions were also included. Hence, the overall environmental impacts include the energy consumption and GHG emissions estimated at different stages.

5.2.2 Life Cycle Inventory

5.2.2.1 Raw Materials and Manufacturing

Life cycle inventory data for raw materials production and manufacturing stages were accessed from the Economic Input-Output Life Cycle Assessment (EIO-LCA) tool developed by Green Design Institute at Carnegie Mellon University (2008).

Environmental impacts inventory for raw materials and manufacturing stage is correlated to direct and indirect monetary activities interacting between different services and sectors. The EIO-LCA model can estimate the relative emissions and demands due to monetary activities in the sector as well as in the supply chain, thus, it is able to include estimations from raw materials production, processing, assembling and manufacturing stages. The unit prices (in US dollars) for each appliance were assumed as $600, $220 and $35 for clothes washer, toilet, and shower head, respectively. The input dollar values in the EIO-LCA model were adjusted from current price to previous values using Consumer Price Index (U.S. Bureau of Labor Statistics, 2011). The inventory for the standard type appliances used in the U.S. National Producer Price Model in 1992 and the inventory for efficiency type appliances (assuming manufactured in 2010) were projected based on the models used in 1992, 1997 and 2002.

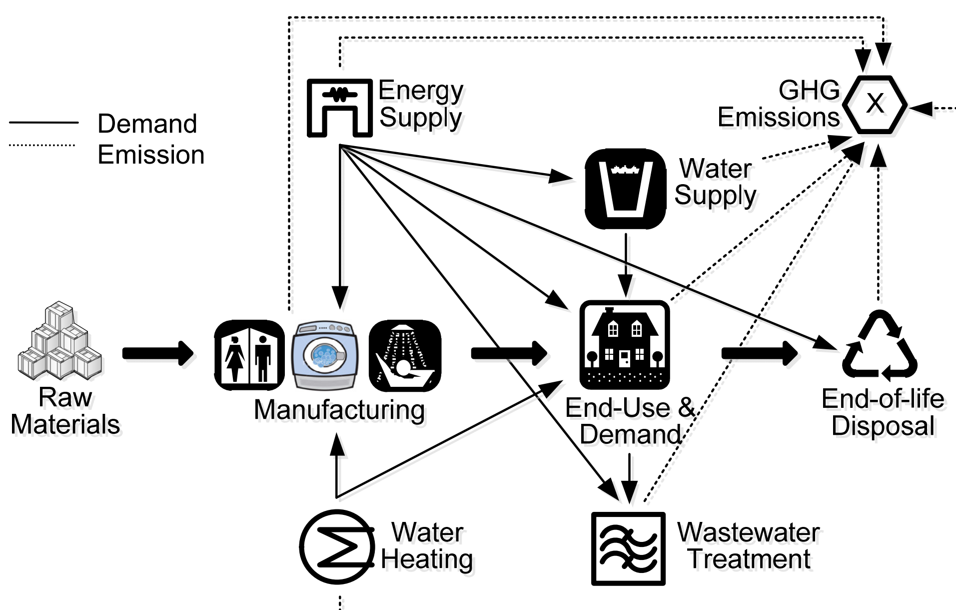

Figure 5.1 Interaction of demands and emission of water efficiency appliances from life cycle perspectives

5.2.2.2 End-use and Demand

The inventory during the end-use and demand stages consider direct energy consumption, indirect energy consumption and GHG emissions associated with the water demand of individual appliances and processes. Water consumption for different water-using appliances in this study is presented in Table 5.1 (Anand and Apul, 2011; Davis, 2008; Lee et al., 2011b; Mayer et al., 1999; Pakula and Stamminger, 2010). The table lists assumptions used for estimating the water demands such as total use cycle and annual consumption of the individual appliances.

The direct energy consumption by clothes washer comes from the electricity use, water supply and wastewater treatment. Direct electricity consumption for clothes washer motor uses is 0.79 MJ/cycle and 0.36 MJ/cycle for standard and efficiency models, respectively (Davis, 2008). Electricity consumption for various processes in the water systems, including water supply and wastewater treatments is provided in Table 5.2 (Lundie et al., 2004; Racoviceanu et al., 2007; Vince et al., 2008).

Energy demands and GHG emission associated to water heating are also considered in the end-use phase. This study assumes only electric water heater (with 90.5% efficiency) is used for heating water. For water use in clothes washer, 14% of customers use hot water (with 42 ◦C increase), 49% of them use warm water (with 20 ◦C increase) and 37% of them use cold water (no increase in water temperature) (Bole, 2006). Water temperatures most frequently used in clothes washer and showering are 15 to 48 and 40 to 49 ◦C, respectively (Pakula and Stamminger, 2010). Percentage of hot water (67 ◦C) to total showering water consumption is assumed as 60% (deMonsabert and Liner, 1998). Energy consumption for water heating can be calculated from the following equation:

$$E = \frac{mc\Delta T}{\eta} \tag{5.1}$$

Where, E is the required energy for water heating (kJ); m is mass of water (L); c is specific heat of water at 25^{o}C (4.181 kJ/L/^{o}C); ΔT is difference of water temperature (^{o}C); η is the efficiency of heating system.

For the GHG emissions inventory associated with the electricity consumption, only carbon dioxide is reported in this section since the concentrations of other GHG are relatively low in comparison to levels of carbon dioxide. The total GHG emissions (in metric tons, mt) can be calculated from the emission factors (EF) and energy consumption as follows:

$$\text{GHG emissions (mt } CO_2\ e^{-}) = \text{EF (mt } CO_2\ e^{-}/\text{GJ)} \times \text{Consumption (GJ)} \tag{5.2}$$

The average GHG EF in the US is 0.188 mt CO_2 e^{-}/GJ. The estimated GHG EF is based on average emissions intensity of total electric sector generation and includes transmission and distribution losses incurred in delivering electricity to point of use (U.S. Energy Information Administration, 2007)

Table 5.1 Per household water consumption for appliances in end-use and demand stage

Appliance	Cycle[a] (unit/year)		Consumption (liter/cycle)	Annual consumption (thousand liter)	Fraction to total water consumption [b] (%)	Reference
Clothes washers[c]	392	Standard	144.6[d]	56.7	19.8	Pakula and Stamminger, 2010 Davis, 2008
		Efficiency	89.7[e]	35.2	14.8	
Toilet	5161[f]	Standard	11.4[g]	58.6	20.5	Anand and Apul 2011; Mayer et al., 1999; Lee et al., 2011
		Efficiency	4.8[g]	25.0	10.5	
Showerhead	766[h]	Standard	9.8[i]	51.3	17.9	Mayer et al., 1999; Lee et al., 2011
		Efficiency	5.7[i]	37.0	15.6	

[a] Household size: 2.8 people
[b] Total water consumption per household: 651 L/household for Efficiency, 784 L/household for Standard
[c] Clothes washers: Electric water heating without drying
[d] 144.6 L = 39.4 L of hot water + 105.2 L of cold water
[e] 89.7 L = 16.3 L of how water + 73.4 L of cold water
[f] assume 5.05 flush per capita per day
[g] liter per flush
[h] assume 0.75 times of shower per capita per day
[i] liter per minutes (6.8 minutes for standard; 8.5 minutes for efficiency)

Table 5.2 Electricity consumption in water supply and wastewater treatment processes

Process	Electricity consumption (kJ/L)	
	Literature	This study
Water Supply		
Raw water pumping	0.18-3.60[a]	1.87
Conventional fresh water treatment (filtration)	0.18-0.54[a] 1.48[b]	0.83
Chemicals production	0.36-1.44[a]	0.90
Potable water distribution	0.72-2.88[a] 3.46[b]	2.09
Wastewater Treatment		
Sewage system	1.01	1.01
Sewage treatment	1.48-3.60[b] 2.38[c]	2.52

[a] Vince et al., 2005
[b] Lundie et al., 2004
[c] Racoviceanu et al., 2007

5.2.2.3 End-of-life Disposal

Approximately 85 to 90% of household appliances are recycled in the US. For all the appliances considered in this study, 87.5% (by weight) of the materials were assumed to be recycled and the rest were landfilled (Bole, 2006). The estimated electricity consumption for the landfilling (including collection and equipment operation) and the recycling activities (including shredding, pelletizing and residual disposal) are 0.613 MJ and 1.530 MJ per kg of materials, respectively (Denison, 1996). The estimated GHG emissions for the landfilling and recycling activities are 0.117 kg CO_2 e^- and 0.098 kg CO_2 e^- per kg of materials, respectively (Denison, 1996; McDougall et al., 2001).

5.2.3 Lifespan of Appliances

Lifespan is defined as the useful time of the appliance before it is replaced while it is most environmentally beneficial. The lifespan calculation is adopted from Chalkley et al. (2003) and it is expressed as follows:

$$n = \sqrt{\frac{2m}{r}} \tag{5.3}$$

where, n is lifespan of an appliance (years); m is fixed energy consumption (GJ); r is the gradient of energy savings at present year.

Different from the assumptions in Chelkley et al. (2003), in this study, the fixed energy consumption considered includes raw material production, manufacturing and end-of-life disposal stages. For the energy savings, direct savings from the end-use stage and associated savings from the water system were considered.

5.3 Results and Discussions

5.3.1 Life Cycle Impact Assessment and Interpretation

The results of the life cycle impact analysis for appliances with standard and efficiency models are presented in Table 5.3. Based on the nature and design of a product, full life cycle environmental impacts of the resources (i.e., energy consumption) and associated GHG emissions in different phases were estimated. Energy consumption from electricity, coal and natural gas were converted to energy equivalent in joules and included in the calculations. Also, the GHG emissions included other potential GHG emissions such as methyl and CFCs. Figure 5.2 and 5.3 present the distribution of energy consumption and GHG emissions, respectively, during different life cycle stages for individual water-using appliances.

5.3.1.1 Raw Materials and Manufacturing

Environmental impacts from the raw materials and manufacturing phases are correlated with the type and nature of materials and processing activities. In the raw material and manufacturing stages, technological advances resulting in reductions in material or energy use are the key factors that reduce the impacts of the products. As shown in Table 5.3, the percentage change in energy use between standard and efficiency models can be as high as 30% (toilet); and, the percentage change in GHG emissions for toilet is near 50%. This suggests that the ceramic industry for toilet manufacturing may have experienced significant improvements in production process.

In the results of raw material and manufacturing stages (Table 5.3), the gap of energy use and GHG emissions between clothes washer and toilet are found to be lower than the expected theoretical values based on the differences in product weight and manufacturing costs. Cloth washer machine contains approximately 65% (in mass) of steel and 16% (in mass) of polypropylene (Bole, 2006), and toilet contains approximately 95% ceramic. Raw materials transformation industries (i.e., primary metals and ceramic) are considered as energy-intensive manufacturing industries which involve electric energy for facility operation and thermal energy for raw material transformation (Nicoletti et al., 2002; Worrell et al., 2001). For cloth washers and toilets, both energy consumption and GHG emissions during the manufacturing stage were significant, contributing more than 50% of the totals in the life cycle (Figure 5.2 and 5.3). In contrast with, the energy use and GHG emissions for showerhead are relatively low (less than 10%) in comparison to the other two appliances because of the nature of materials (plastic) and light weight of the appliance.

5.3.1.2 End-Use and Demand

Environmental impacts (energy consumption and water demand) from end-use and demand stages are most significant within the water system. Range of energy use and GHG emissions during the end-use and demand phases varies depending on appliance type and services (Figure 5.2 and 5.3). In this study, three water-using appliances are included in the analysis. Both of them separately represent different natures of appliances (i.e. toilet consumes cool water only; showerhead requires additional indirect energy use for water heating; and cloth washer consumes both direct and indirect electricity and water demand). The variations in energy demand are partially due to the energy uses for water heating.

As shown in Table 5.3, the total energy consumption for showerhead is similar to that for clothes washer, which can be explained by the summation of energy uses during manufacturing and water heating stages (i.e., one has higher use in manufacturing but lower use in water heating and the other is the opposite). Energy consumption for water heating is the indirect source of electricity consumption in the water system. Hot water accounted for 21% of the total residential secondary energy use (Eggertson, 2005) or 15% of the total residential energy use. As a result, energy demands for hot-water-intensive appliances account for significant fractions of total demand during the end-use phase (73% for cloth washer and 93% for showerhead) (Figure 5.4). Consequently, reducing the consumption of hot water is expected to reduce the associated environmental impacts (Racoviceanu and Karney, 2010).

By reducing water consumption at end-use phase, the overall water-related energy burden is expected to be greatly improved (i.e., difference between standard and efficiency models). In the water system, electricity consumption and GHG emissions related to facility operation (include pumping) has the most significant contribution to total energy consumption and GHG emissions. By contrast, the energy consumption and GHG emissions from transportation-related process (e.g., transportation of chemicals) are insignificant (Racoviceanu et al., 2007).

Environmental impacts from water supply and wastewater treatment process ranges from 7% to 18%, depending on type of appliance (Figure 5.2 and 5.3). Water supply requires most energy for pumping raw water to the potable water treatment location and distribution to the community (Table 5.2). Therefore, the energy demands for water supply are greater (approximately 38%) than that for wastewater treatment (Figure 5.4). However, energy demands for water supply does not vary significantly between appliances since all of them have remarkable water demand (Table 5.1).

In the wastewater treatment system, most of the energy demand is for chemical production and treatment process. Recent regulation on wastewater treatment plants have focused on nutrient (nitrogen and phosphorous) removal and consequently increased the resource demands and environmental emissions (Foley et al., 2010).

5.3.1.3 End-of-life Disposal

All of the water-using appliances in this study are made with recyclable materials. Majority (87.5% by weight) of the materials were assumed to be recycled with the rest is to be landfilled during the end-of-life disposal stage. Therefore, in this study, only energy consumption related to recycling and landfilling facility operation were considered; however, the energy recoveries from remanufacturing of recycled materials were excluded. The energy consumption for remanufacturing of recycled materials can be complicated with the extraction procedures to separate impurities.

Recycling usually consumes more energy than landfilling. In the recycling facility, the recycled appliances are processed with different procedures such as shredding and pelletizing, which require significant amount of energy. By contrast, the energy use in landfilling is relatively low which considers only equipment operation for depositing the waste. The energy use and GHG emissions for all appliances during disposal stage are proportional to the body weight of the individual appliances. Thus, the values for clothes washers are about twice of the values for toilets (Table 5.3). Disposal stages for all appliances account for a very small portion (especially for showerhead) of the energy use and GHG emissions during the life cycle (Figure 5.2 and 5.3). However, the contributions during disposal stage are not negligible for the mid-size appliances, particularly for clothes washers and toilets.

Table 5.3 Life cycle assessment comparison for energy consumption and GHG emissions

Appliance	Clothes Washer		Toilet		Showerhead	
	Standard	Efficiency	Standard	Efficiency	Standard	Efficiency
Energy Use (GJ)						
Raw Materials and Manufacturing	3.701	3.108	2.330	1.623	0.207	0.162
End-Use and Demand						
Water supply	0.322	0.200	0.333	0.142	0.292	0.210
End-use	0.310	0.141	0.000	0.000	0.000	0.000
Water heating	2.997	1.240	0.000	0.000	5.968	4.304
Wastewater treatment	0.200	0.124	0.207	0.088	0.181	0.130
End-of-life Disposal	0.127	0.127	0.064	0.064	0.000	0.000
Total	7.658	4.940	2.934	1.917	6.648	4.807
GHG emissions (mt CO_2 e^-)						
Raw Materials and Manufacturing	0.272	0.217	0.181	0.091	0.015	0.010
End-Use and Demand						
Water supply	0.061	0.038	0.063	0.027	0.055	0.039
End-use	0.058	0.026	0.000	0.000	0.000	0.000
Water heating	0.563	0.233	0.000	0.000	1.121	0.808
Wastewater treatment	0.038	0.023	0.039	0.017	0.034	0.024
End-of-life Disposal	0.009	0.009	0.005	0.005	0.000	0.000
Total	1.000	0.546	0.287	0.139	1.225	0.882

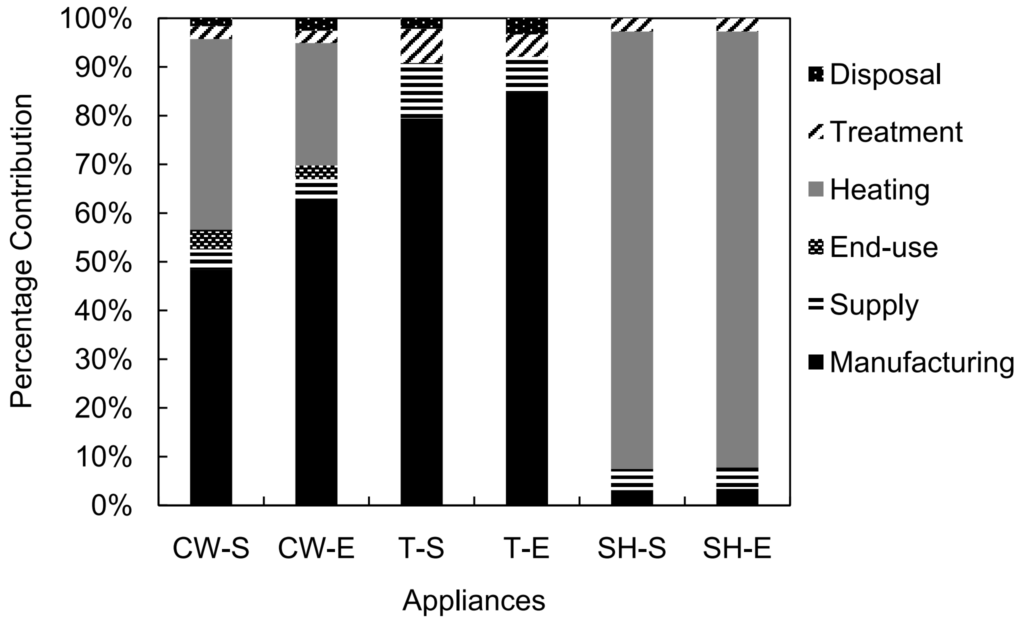

Figure 5.2 Distribution of energy consumption to LCA processes and services (CW: cloth washer; T: toilet; SH: showerhead; S: standard; E: efficiency)

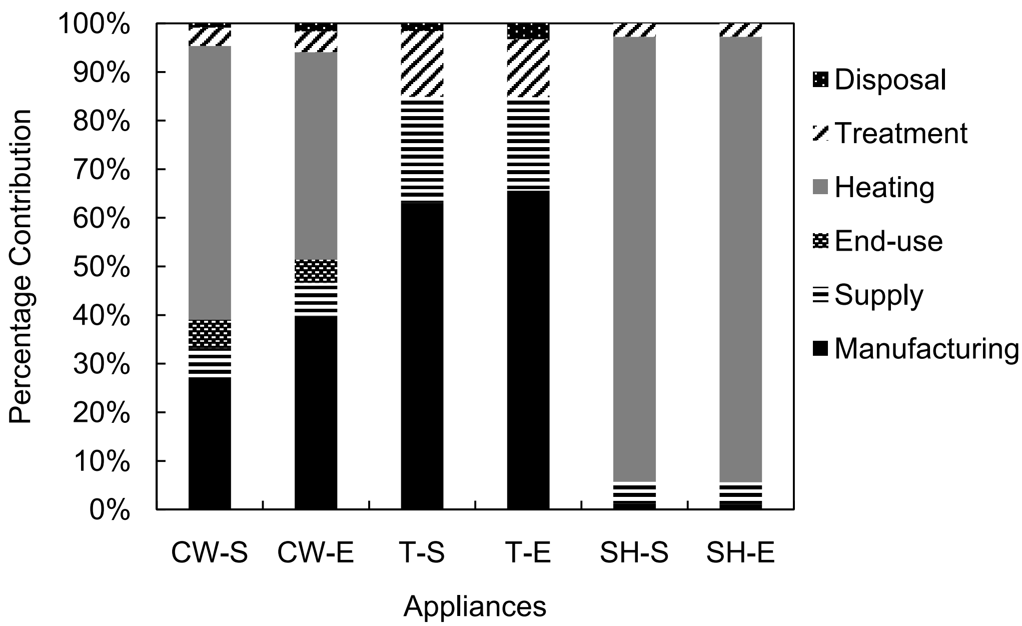

Figure 5.3 Distribution of GHG emissions to LCA processes and services (CW: cloth washer; T: toilet; SH: showerhead; S: standard; E: efficiency)

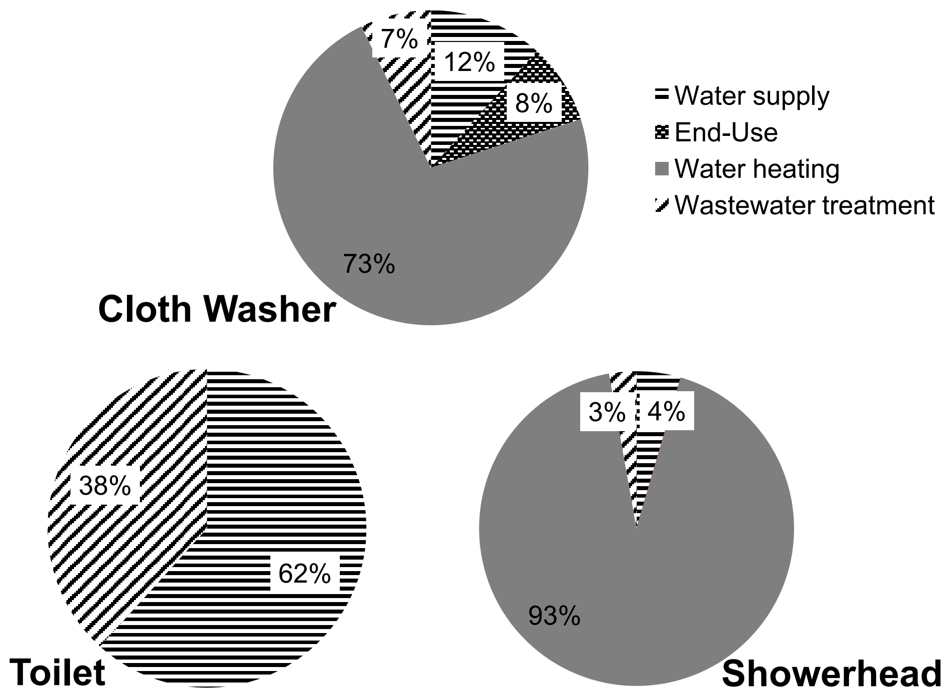

Figure 5.4 Energy consumption distributions for end-use and demand phases of efficiency models appliances

5.3.2 Lifespan Optimization

The purpose of lifespan optimization is to minimize the environmental impacts from a product by reducing resource consumption, pollution emissions and waste generation. For a product with short lifespan, it would be beneficial to upgrade its design to use environmental friendly materials that will cause less impact upon disposal. For a product with long lifespan, the major effort should be placed for improving its reliability and maintenance (Chalkley et al., 2003).

Estimated optimized lifespan from energy consumption balances are 9.9, 20.7 and 8.2 years for cloth washer, toilet and showerhead, respectively, as presented in Table 5.4. The operation lifetime for water conservation practices have been reported in literature as

20 to 25 years for toilets, 12 to 14 years for cloth washers, and 10 to 12 years for showerhead and faucets (Gleick et al., 2003; Koomey et al., 1999; Vickers, 2001). Toilet has the longest lifespan (20.7 years) because it does not require energy to operate; as a result, the optimal lifetime estimated in this study is very close to the value reported in literature (20 to 25 years). The results suggest that optimum lifespan of appliances using energy consumption as the criterion are estimated to be lower than those using product cost as the criterion (Kim et al., 2006).

Two different values of optimal lifespan were found for showerhead: 2.2 and 8.2 years for with and without consideration of water heating, respectively. The gradient of energy savings (r) is large while considering energy consumption for water heating into calculation, consequently, decreases the lifespan of showerhead. The fraction of fixed energy consumption from manufacturing and end-of-life disposal stages are relatively small in comparison to the consumption during end-use and water heating stages (Figure 5.2). Thus, a small change in gradient of energy savings can result in significant differences in life span (from 2.2 to 8.2 years).

The results indicate that the appliances should have a shorter replacement cycle in order to minimize the environmental impacts brought by the product. Policies for earlier replacement of older household appliances with efficiency models should be encouraged for environmental sustainability purposes which is a similar finding reported by other studies (Kim et al., 2006; Young, 2008).

Table 5.4 Comparison of estimated life span for appliances

Appliances	Estimated lifespan (years)		Reference
	This study	Literature	
Cloth washer	9.9	10-14	Young, 2008; Koomey et al., 1999; Gleick et al., 2003
Toilet	20.7	20-25	Vickers, 2001; Gleick et al., 2003
Showerhead	2.2[a] or 8.2[b]	10-12	Koomey et al., 1999; Vickers, 2001

[a] considering energy consumption for water heating
[b] without considering energy consumption for water heating

5.4 Conclusions

Environmental impacts of three water-using appliances were analyzed from raw material manufacturing to end-of-life disposal using LCA approach. For the analysis in different life cycle phases, both clothes washers and toilets had significant environmental impacts during raw material and manufacturing stages due to the energy-intense industries for materials used to manufacture these appliances. Disposal only attributed to very small portion (especially for showerhead) of environmental impacts in the total life cycle impacts. However, their contributions should not be neglected due to the energy-intensive processes used for recycling materials. For the water system, water supply requires the most energy for pumping. Therefore, the environmental impacts for water-using appliances in water supply are greater than those in wastewater treatment. The impacts form water supply does not significantly vary among the appliances evaluated since all of them involve high water demand. Environmental impacts are high for water heating, particular for showerheads, while the impacts from other phases are relative small.

The LCA approach has used to estimate the optimum lifespan of water-using appliances. Energy demands in fixed (manufacturing and disposal) and variable (end-use) stages were used in estimating the optimum use time. The results indicate that the estimated optimum lifespans using life cycle energy demand as the optimization criteria are slightly lower than those using product cost as the criteria. The results also indicate that earlier replacement of lower efficient models with higher efficient models would minimize the environmental impacts of the product. This paper concludes that the water-using appliances, in this study, have significant impacts on the environment from both water and energy perspectives. Therefore, strategies for replacing or retrofitting of the appliances can provide significant benefits for water demand management and urban sustainability.

CHAPTER VI

CONCLUSIONS

6.1 Summary

This dissertation aims to understand the potential benefits to the environment by implementation of residential water conservation practices. Each chapter included in this dissertation attempts to cover the hypotheses and objectives proposed in this study. As demonstrated in previous chapters, several statements regarding the assessment of water conservation practices can be addressed as the following:

1. ***The proposed water conservation practices are effective in terms of water savings.*** Household water demand significantly decreased (6 to 10%) in the first two years of implementation, and there were continuing effects in the following years. Among all of the proposed practices, high efficiency toilets and clothes washers posed highest potential for conserving water. Moreover, implementation of multiple types of high efficiency appliances can greatly increase the household water savings.

2. ***The proposed water conservation practices are significant in determining residential water demand.*** All the proposed water conservation practices have shown remarkable contributions in reducing residential water demand. The contributions in water savings for different water conservation practices were highly dependent on user characteristics and habits. High efficiency aerators indicated the highest water saving potential, based on its 19.7% reduction in water demand. However, There was not sufficient evidence to conclude that the reduction in water savings were correlated to the quantity water conservation practices adopted.

3. ***Implementation of proposed water conservation practices can reduce overall environmental impacts.*** Significant differences (up to 35%) in overall environmental impacts (energy demand and greenhouse gas emissions) were found between standard type and efficiency type appliances. The reduction of environmental impacts can be attributed to two major components in the life cycle assessment. First, implementation of water conservation practice can significantly reduce both water and energy demand of each practice. Moreover, the technology improvements for raw material transformation industries greatly reduce the energy demand in the manufacturing stage.

6.2 Recommendations to Sustainable Management Strategies

This dissertation also intends to have recommendations for sustainable management strategies based on the findings discussed in the chapters. Therefore, the recommended strategies are defined into three major perspectives:

1. ***Additional efforts are needed for lower water demand level.*** Although the proposed residential water conservation practices are effective in reducing household water demand, further investments on other potential water conservation practices are still needed in order to lower future water demand in a community. Suggestions of future potential water conservation practices are discussed in section 6.3.2.

2. ***Alternative resources of renewable energy are needed for minimizing environmental impacts.*** Use of fossil fuel usually causes concerns in environmental pollution and global warming. Therefore, most of the energy-related studies were targeting to renewable energy technologies which apply natural resources (such as sunlight, wind or tides) as energy sources. The applications of renewable energy can

reduce the consumptions of electricity or fossil fuel, and, as a result, minimize the associated environmental impacts.

3. ***Optimal lifespan of a practice should be considered for the time frame of replacement.*** Early replacement with efficiency models is encouraged in order to minimize the environmental impacts brought by the product. However, the time of replacement should not be shorter than the estimated optimal lifespan, which can ensure the environmental impacts in raw materials and manufacturing stages of the product have been paid off.

6.3 Future Study Recommendations

6.3.1 Water Footprint

The water footprint concept was first introduced by Hoekstra and Hung (2002), which is a consumption-based indicator of water use defined as total volume of water needed for the production and consumption of goods and services as well as the water directly consumed by the residents of the community. Four factors that most influence the water footprint determination are: total volume of consumption, consumption patterns, climate change and conservation practices (water use efficiency) (Hoekstra and Chaoagain, 2007; Yu et al., 2010). Future studies can focus on characterization of influence factors and improvement of water footprint analysis with a combination of input-output analysis and quantification of virtual water flows.

6.3.2 Alternative Sustainable Environmental Practices

Environmentalists have worked on developing sustainable environmental practices to ensure environmental sustainability in the near future. Based on the results in this study, other alternative sustainable practices are still needed to achieve the goals. In addition to promoting water conservation practices to residential customers, delivery of the practices to water-intense industries (i.e., hotels and restaurants) should be targeted to decrease total water demand. Targeting water conservation to hotel and restaurants may contribute to a significant amount of water savings since economy in the urban areas are based on tourism. Other potential water and energy conservation practices are discussed in the following sections.

6.3.2.1 Other Water Conservation Practice: Soil Moisture Sensors

Soil moisture sensors can control occurrence of irrigation event (watering or bypassing) by determining real time soil moisture content at a defined set point. The use of soil moisture sensors has shown benefits to residential households by reducing irrigation water use more than 40% (McCready et al., 2009; Quails et al., 2001) Other potential environmental benefits from installation of soil moisture sensors also include: maintaining optimum soil moisture saturation to minimize plant wilting, and assisting deeper plant root growth to reduce runoff (Clark, et al, 2008).

6.3.2.2 Other Water Conservation Practice: High Efficiency Cooling Tower

There are two major means for water saving on cooling towers. The most popular method for conserving water use in cooling towers is to reduce the amount of makeup water by increasing the cycles of concentration. Other methods like recovering

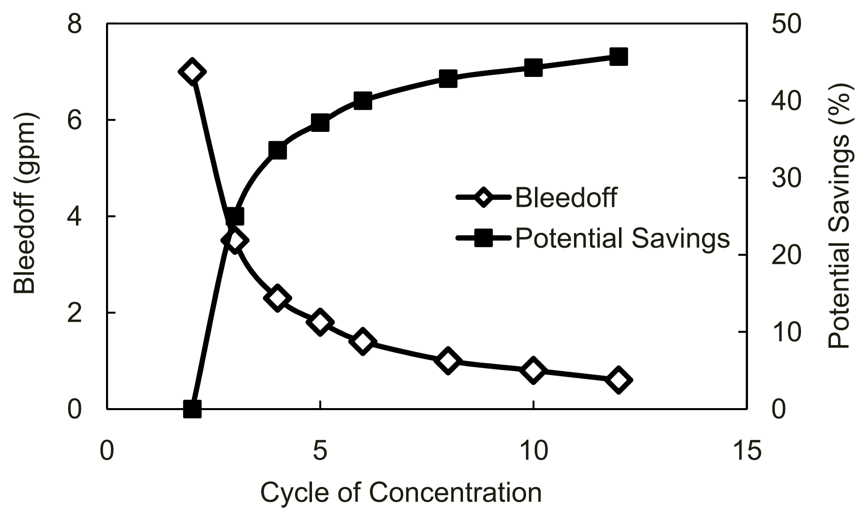

Figure 6.1 Relationship of cycle of concentration between bleedoff flow rate and potential savings for a single 300 tons cooling tower

condensate or evaporation water are expected to save significant amounts of water. Figure 6 presents the flow rate of bleedoff and potential water savings in various operations of cycle of concentration. The flow rate of bleedoff is inversely proportional to the number of cycles, which means a certain amount of water could be saved by increasing the cycles of concentration.

6.3.2.3 Other Energy Conservation Practice: High Efficiency Water Heater

Approximately 15 percent of the energy consumption in a household comes from water heating. According to the results in Chapter V, energy demands for hot-water-intensive appliances account for significant fractions of total demand during the end-use phase. Reduction of hot water consumption and energy demand for heating are expected to reduce the associated environmental impacts.

The high efficiency water heater can be divided into two types: with storage tank and tankless. Comparison of different type of high efficiency water heaters are listed in Table 6.1 (Energy Star, 2011). The storage tank type high efficiency water heater utilizes insulated storage tanks to keep hot water ready for use. But there will be some energy losses (standby losses) for keeping water hot all the time. The tankless type high efficiency water heater uses coils to have water circulated and heated. This eliminates the standby losses inherent in the storage tank type water heater. The possible limitation of the tankless type water heater is that the hot water supply may be insufficient if many fixtures use hot water simultaneously.

A solar water heater is another alternative choice. It can reduce operating energy requirements by up to 90 percent. The latest development in solar water heating system is to combine solar heating panels with solar water pumps which can minimize the operational energy consumption for heating and pumping (Roonprasang et al., 2008). Residents living in tropical or subtropical areas should take advantage of solar energy with in combination with high insolation.

Table 6.1 Comparison of high efficiency water heaters

Type	Energy Savings (%)	Best Climates	Expected lifetime (years)	Major Advantages
High Efficiency Storage Tank	10-20	Any	8-10	Lowest initial cost
Tankless Water Heater	45-60	Any	20	Unlimited supply of hot water
Heat Pump	65	Mild-Hot	10	Most efficient electric fuel option
Solar Water Heater	70-90	Mild-Hot	20	Largest energy savings

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