Water Use Behavior in Single-Family Homes: A Case Study in Texas

Peng Xue[1,2], Tianzhen Hong[3], Bing Dong[4]
[1]Beijing Key Laboratory of Green Built Environment and Energy Efficient Technology, Beijing University of Technology, China
[2]Beijing Key Laboratory of Green Built Environment and Energy Efficient Technology, China
[3]Building Technology and Urban Systems Division, Lawrence Berkeley National Laboratory, USA
[4]Department of Mechanical Engineering, University of Texas at San Antonio, USA
Corresponding Author: Tel.: +86 18813030116; E-Mail: xp@bjut.edu.cn

Abstract

Residential water use has become a critical issue of the built environment due to drought and increasing water retail price in many regions around the world. However, there is limited research done to understand water use behavior in residential buildings. This paper presents data analytics and results from monitoring data of daily water use in 50 single-family homes in Texas, USA. Based on data analysis, residents' regular water use patterns are investigated. The results help generate awareness of water use behavior and support further studies in clustering water use behavior patterns and developing water use models for simulation.

Introduction

Most countries around the globe are experiencing a water crisis today. One-third of the global population lives without access to a toilet. A number of people equal to twice the population of the United States live without access to safe water (WHO and UNICEF 2015). Drought conditions in the United States, including threatening drought in California over the last four years, are causing a re-examination of the value of water. Several western states in the United States are surviving the most severe drought conditions in history, with normal, seven-day average stream flows at "extreme hydrologic drought" and "severe hydrologic drought" levels (USGS 2015). The latest 5-year report of the U.S. Geological Survey (Maupin et al. 2010) indicates that total domestic water use, including self-supplied withdrawals and public-supply deliveries, was at 103,709 million liters a day in 2010, with California and Texas ranked the first two in the total water withdrawals among 50 states. As a nation overall, average domestic daily water use (DWU) per capita is reported as 333 liters (88 gallons), which includes potable and non-potable water and includes both indoor and outdoor use. The average per capita use for total domestic water use decreases 10% in last five years and it still represents potential for water conservation (Maupin et al. 2010). Significant energy and associated cost savings are also possible with the reduction in water demand (Malinowski et al. 2015).

Studies over the last decade found that domestic water use is related to many factors. In an Arizona study, Balling et al. (2008) claimed that 70% of household monthly variance in water use could be explained by atmospheric conditions in the state. In a Korean study, Praskievicz and Chang (2009) confirmed that the weather condition plays a key role in water use in that country. Water pricing policy was shown to have influence on single-family residential water use (Polebitski et al. 2010). A study by Wentz et al. (2014) showed that the age of residents was not a significant factor affecting domestic water use, while another study showed that the number of teenagers was a key variable of indoor water use (Aquacraft 2015). Rosenberg and Madani (2014), in their editorial, suggested that there is a need to think how water interacts with energy. Household water and energy use are heterogeneous and skewed with large variations among households, but individual appliance shows great energy-water linkage (Abdallah and Rosenberg 2012).

Water use characteristics can only be observed and recorded by a person with relatively long intervals before the installation of data loggers. The output could be just the descriptive results such as the DWU per capita (Bullock et al. 1980) and the hourly water use per household (Papakostas et al. 1995). During the mid 1990s, researchers in Boulder, Colorado, started using data logging technique in data collection. (DeOreo and Mayer 1994, DeOreo et al. 1996). With this technique, a computerized sensing device is attached to the water meter and measures flow into the house at 10-second intervals. This makes it possible to obtain and analyze good resolution of water use data from a larger sample.

End-use analysis includes disaggregate water use into end-use components, such as bathing, washing clothes and dishes, and flushing toilets, etc. In a well-known study, Residential End Uses of Water (REUWS), published in 1999 by the Water Research Foundation and the American Water Works Association, researchers showed that the average DWU of 262.3 liters per capita per day (lpcd) in single-family homes goes into eight end-use components: toilets, faucets, leaks, clothes washers, dishwashers, showers, baths, and other (Mayer et al. 1999). Other studies (DeOreo et al. 2011) show similar findings, which are essential for establishing benchmarks (Mayer 2009) and developing water devices. Other research shows that introducing engineered water efficiency devices could reduce indoor water use by 35% to 50% (Inman and Jeffrey 2006).

Occupant behavior-related water use in residential buildings is a critical issue for water conservation and water use prediction. Occupant behavior is complex and stochastic, causing a high DWU variability both among residences and within the same residence (Lutz 2012). Corral-Verdugo et al. (2003) found that general beliefs could influence specific water beliefs, and in turn could affect water consumption. Willis et al. (2010) investigated the effect of visual display monitors on residents' shower behavior; results confirmed a significant effectiveness with 27% reduction in a shower water use event. Consumer behavior may also be negatively affected by water-saving devices. Inman and Jeffrey (2006) found that residents took longer showers and consumed more water after installation of water-saving devices, due to the belief that their water-saving devices would save water (rebound effect).

To predict water use, a demand model needs to be developed. Chu et al. (2009) proposed a framework of residential water demand with correlations among variables, but much work remained to be explored. Chang et al. (2010) also developed a water demand framework that incorporates existing factors with urban development policies. Analytical, hybrid, and regression models have been tested for characterizing the households' water saving by retrofits (Suero et al. 2012). New demand models based on empirical data have been tested to predict better results (Aquacraft 2015). However, most existing studies on water use behavior models are observed from the perspective of use time of water-consuming devices and lack in-depth behavioral analysis. While energy-related occupant behavior has been studied extensively for residential and commercial buildings (Hong et al. 2015; Yan et al. 2015), water use behavior is under-researched. Aiming to provide insights into household water use behavior, this paper presents analytical results from monitoring data of DWU in 50 single-family homes in Texas, USA, as well as exploration of possible reasons behind household water use behaviors.

Methodology

Database

This study uses data collected through a project by Pecan Street, Inc. (https://dataport.pecanstreet.org/), which is the world's largest source of disaggregated customer energy and water use data. The data are stored in 25 tables in a SQL database, which consists of weather data, water use, audits, annual surveys, energy consumption and other information (e.g., gas use). The Pecan Street database includes 1338 houses, 1105 of which are still active. The database started collecting data January 1, 2011, and continues up to the time of this study (September 26, 2015). Energy data is recorded in 1-minute time intervals, while water use is recorded as daily sum before May 10, 2013, and by minute from then on.

In this study, household information comes from the survey tables. DWU value is calculated from the water usage table, which shows a household's total water use within a specific time interval (by day or minute). Energy consumption data are from the hourly energy-use table, which contains 67 columns showing energy consumptions of different appliances in a house. Water use data in the database is sparse and not always continuous. After data processing (excluding the ones without water use data), 50 single-family houses are selected for this study.

Data processing

The big data of houses were first downloaded from the database as comma-separated-value (CSV) files. The main purposes were to calculate the DWU and daily energy use from the cumulative data (by hour and minute) for each house, and to convert units of the measured data. All pre-processed data were further processed in the following steps.

The second step was to clean all the translated data obtained from the previous step, which includes summarizing all household data into one sheet with outdoor air temperature in chronological order and removing data (cumulative raw data) with gaps of more than one day.

After the translating and cleaning steps, 11852 logging data points for 60 houses were collected in one Excel sheet. Some zero values of DWU were also included, which reflected that no residents were home and consumed no water on those days. As the zero values may have a significant influence on calculating the average and DWU values, small values such as 0 and 1 liter/day were excluded in the study of water use behavior. After applying the above criteria, 10 of the households with valid data had data for less than a month. These 10 households were excluded from the originally selected 60. In the end, water use data for the remaining 50 households were used in the study.

After all data were pre-processed, a dataset of 10659 valid DWU values from 50 houses was built. Combined with the house information, the data were summarized by different objectives and shown in Table 1.

Analysis procedure

The first step of the analysis procedure is to investigate the time and frequency distribution of DWU of a typical house. Further relation between DWU and outdoor air temperature, day of the week, and season are also studied. A sudden (anomaly) peak of DWU is found as a common phenomenon in many homes, which will be discussed with leakage, water intensive use and residents' habit in the Discussion section. The second step is to generate generic results using normalized data from all 50 homes, to find water use patterns between weekdays and weekends, and to establish a baseline model of DWU for single-family homes. By comparing the results among different houses, the third step is to find related factors affecting DWU, namely residents' income, education, age and daily activity. The information for all of the selected 50 households is shown in the appendix (except for the exact house ID which was anonymized due to privacy concerns).

Statistical analysis methods

1) Spearman's rank correlation coefficient

Spearman's rank correlation coefficient is adopted to describe the relationship between two variables by assessing the monotonic function. A perfect value of +1 or −1 occurs when one variable is a perfect monotone function of the other. The coefficient ρ could be computed from:

$$\rho = 1 - 6\sum d_i^2 / n(n^2 - 1) \qquad (1)$$

where d_i is the difference between ranks of two variables; i is the case number; n is the total number of cases. This correlation coefficient was applied to investigate the relationship between the DWU per house and the age groups of occupants in the house.

2) Frequency distribution

In this study, frequency distributions are displayed as graphs that show the frequency of DWU in the whole dataset. A frequency distribution shows a summarized grouping of DWU values divided into mutually exclusive intervals and the number of occurrences in an interval.

3) Median for baseline

Water use distribution should be studied with medians, not averages, as the feature is not symmetrical (Lutz 2012). In this study, median values of all logging data can be obtained in three different ways. The first method is to obtain the median values from all logging data directly, the second method is to calculate them from all household median DWU values, and the third method is to calculate them from all household average DWU values.

The first method chooses the median value from all the data but ignores the fact that the number of data points from each household is not the same (as shown in appendix). The second method is more appropriate, which considers the differences between households and obtains the median values of each house first. However, the median value of a house can only be explained as the most likely condition. The value itself ignores the high water use condition and sudden peak, which should be considered as the behavior of the residents. Therefore, the third method is most appropriate to establish the baseline, which calculates the average values of DWU for each household first and then finds the median DWU for the entire dataset of 50 households.

Result analysis

Statistical analysis of a single house

We started studying the residents' water use behavior in a single house. House No. 7 is selected with the most logging data points—538 days of valid data—from the 50 monitored homes.

With the 538 valid data of DWU, the frequency distribution is shown as Figure 1. The X-axis interval is set as 40 or 75 liters per day (lpd) and Y-axis shows the occurrence number of days.

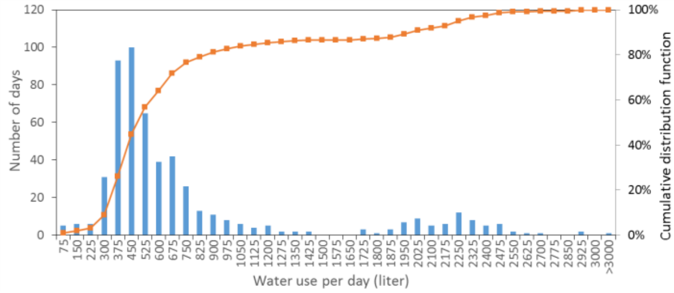

Figure 1: Frequency and cumulative distributions of DWU (House No. 7)

The frequency distribution of DWU shown in Figure 1 is neither symmetrical nor normal distribution. The curve has a long tail, it features a striking peak around 450 lpd, and most of the data are equal or greater than 300 lpd. However, there are still 189 days when the DWUs are much more than the average of 730.28 liters per household per day (lphd). A second peak appears around 2250 lpd, which indicates another behavior pattern of high water use that needs further study. It is worth noting that this is a typical feature of DWU frequency distribution: almost all 50 homes show a distribution with two or three peaks.

DWU differs from day to day and has large variations. Monitored data from House No. 7 are shown in Figure 2 with the X-axis of outdoor air temperature. The dataset grouped by weekdays and weekends is shown in Figure 2a, while it is also grouped in seasons as shown in Figure 2b. The seasons are divided by solstices and equinoxes.

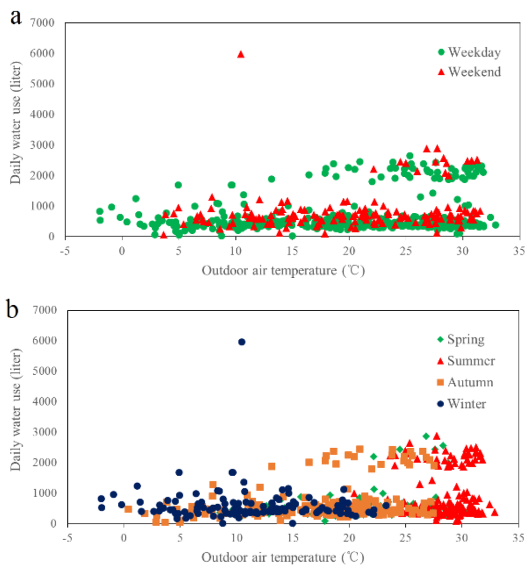

Figure 2: DWU (House No. 7) with outdoor air temperature: a) by weekdays and weekends; b) by seasons

The phenomena of summer peak and the dual peaks in Figure 1 can be reflected as the two-layer feature in this figure. Figure 2 shows that the relationship between household DWU and outdoor air temperature is not linear. However, the two-layer feature indicates that residents keep basic requirements of water use and do not use much water for irrigation when the outdoor air temperature drops below 15℃. As seen from the higher layer in Figure 2a, the high water use behavior occurred in both weekdays and weekends, indicating that the residents have a constant 2250 lpd of water use once or twice a week. Figure 2b shows that the water irrigation behavior has strong seasonality, with the winter months having lower values. The average DWU values from spring to winter are 593.87 lphd, 948.03 lphd, 694.81 lphd, and 607.42 lphd, respectively.

There is also an isolated data point with a very high value in Figure 2, which is more than twice the value of other data points. This kind of anomaly peak happens in almost half of the 50 homes, which may result from water leaks, watering, or filling swimming pools. This anomaly is considered further in the Discussion section.

Statistical analysis of 50 houses

The data show large variations in water use from day to day and from home to home. It is important to normalize the water use for a single-family home on the basis of number of persons living in the home and the total floor area of the house. Figure 3 shows several water use metrics for the 50 homes, including DWU median per household, average DWU per household, average DWU per capita, and cumulative distribution function of DWU per household. The results are sorted by the average DWU per household.

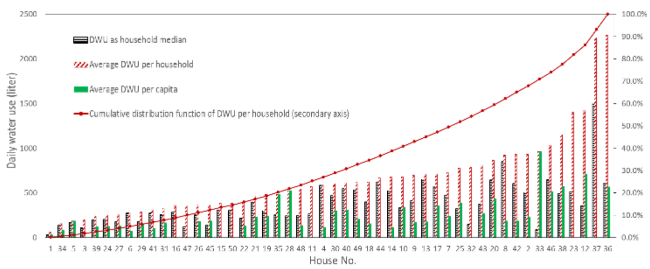

Figure 3: Water use metrics for 50 houses

As seen in Figure 3, the average DWU differs significantly from house to house; the largest two houses reach 2250 lpd. This figure also shows that the top 26% of households use 48% of total water. The overall average DWU of all houses is 676.27 liters, and the median DWU of each house is also shown in the figure, which is less than the average DWU. The median DWU in 95% of the houses is between 90 lphd and 650 lphd. This result reflects the frequency distribution curve of DWU is not symmetrical and the long tail is significant. House No. 36 has a median DWU of 613.17 lphd and an average DWU of 2267.84 lphd. The figure also shows the DWU normalized by the number of residents. The calculated result indicates that nearly 25% of people use 51% of the total water. The overall average DWU per capita is 272.81 liters. The DWU, normalized by capita and square meter, is also provided in the figure, but it can be much higher for small houses.

In conclusion, this study found that it most effective and appropriate to study the chosen data normalized by capita.

These results also show that the Pareto Principle is in operation in this water use study. If high water use households (or people) improve (decrease consumption), water will be significantly saved.

The next analysis had to do with household DWU during the week versus on the weekend. The houses grouped by the types of occupancy are shown in Figure 4, and the average DWU of each house is separated with the average DWUs for both weekdays and weekends.

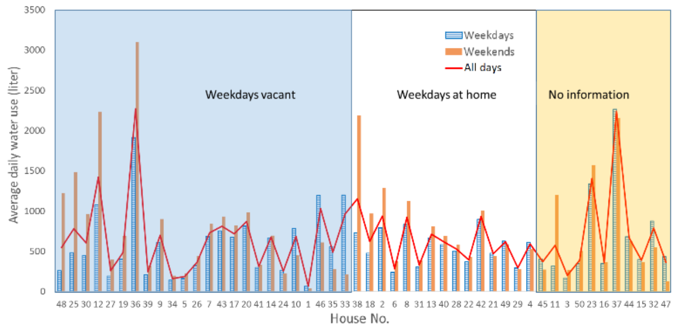

Figure 4: Average DWU during weekdays and weekends for 50 houses among three occupancy types

Figure 4 shows the average DWU values of all houses represented by a solid line. Compared with this solid line, it is clear whether residents use more water during weekdays or not. Average DWU is closer to weekdays DWU since weekdays have a higher weighting factor.

Results of this analysis show that 68% of houses consume more water per day on weekends than weekdays. However, some houses have higher average DWU on weekdays. Considering the occupancy on weekdays, no significant relation can be found. According to results of first two groups in Figure 5, both groups have households using more water on weekdays than weekends. It seems that DWU is less affected by occupancy than by residents' habits.

Looking at all valid DWU data points as a whole, the frequency distribution of all 50 houses is shown as Figure 5. The X-axis interval is set as 40 lpd.

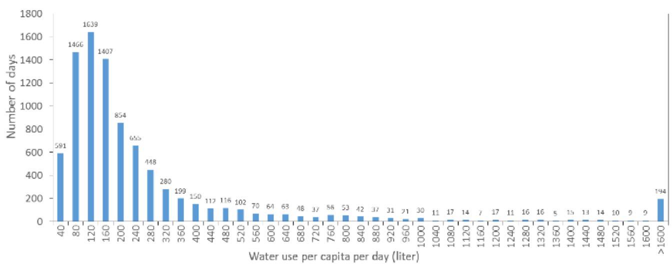

Figure 5: Frequency distribution of DWU among 50 houses

From Figure 5, it can be seen that the distribution curve only has one peak and a long tail. The average water use per capita per day across all 8949 data points is 272.81 lpcd but the standard deviation can be as high as 521.48 lpcd. When studying the baseline, the median value is often adopted as a fair rule. In this study, median value is obtained from all 50 houses' average DWU value (Figure 3); the result is 186.00 lpcd. Therefore, the baseline of the DWU for these households can be set as 186.00 lpcd.

Discussion

Cross comparison of all houses

After being normalized by the number of residents, the DWU of each house can be studied in more detail. The box plot of DWU per capita for 40 houses is shown in Figure 6 as the other 10 houses have no information about the number of residents. The results in Figure 6 are sorted by the median DWU value.

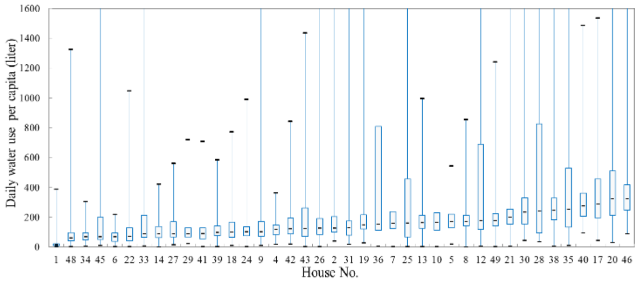

Figure 6: Box plot of DWU per capita for 40 houses sorted by median values

As seen in Figure 6, the median values of DWU per capita among the 40 houses are between 15 liters and 320 liters. The median value of these household median DWU values is 127.76 liters. Focusing on the highest value at each house shows that 50% of households have median DWU values higher than 1500 lpd, which means these data may be experiencing anomaly peak. Some of the interquartile ranges (cubic length) shown in the figure are very big. This result reflects that the residents in some households—namely houses 12, 25, 28, 35, and 36—have frequent high water use behaviors compared to their own average DWU. The detailed DWU results on a long interquartile range will be shown in the next section.

As discussed, the DWU of each household—even the value of DWU per capita—differs significantly. This research next looked at which factors could account for higher water use in some households compared to others, factors including higher personal income, better education, teenagers at home, or washing behaviors. Water use was also compared to energy use to see if energy use somehow correlates to water use.

Income and education

To test assumptions that might explain the correlation between income, education, and DWU, the next analysis normalized DWU and income by the number of residents in each house. The assumption was that residents with higher income may have a higher standard of living and consume more water. The personal income is calculated from house information and grouped in seven levels, as shown in Table 1. The relation between DWU per capita and personal income is shown in Figure 7, with the levels of education presented in different shapes.

Table 1: Personal income levels

Personal income levels	1	2	3	4	5	6	7
Income *per capita* ($)	10k~15k	15k~25k	25k~35k	35k~50k	50k~75k	75k~150k	>150K

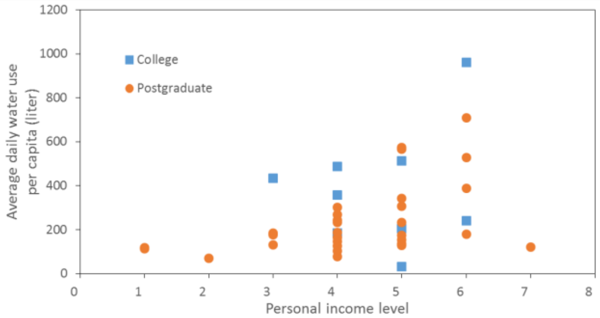

Figure 7: Average DWU per capita with personal income and education

The analysis represented in Figure 7 seems to show that DWU per capita has a positive correlation with the personal income level—residents with higher incomes seem to consume more water. Focusing on the personal income level from 3 to 6, residents with college degrees use more water than the postgraduates, on average. Though the numbers of cases are not equal, people with undergraduate college degrees consume the most in three out of four income levels. Using these 40 cases as a guide, it is reasonable to say that residents with more education are likely to use less water that those residents with less education.

Age group

The next analysis examined the assumption that teenagers use more water than other age groups. It is difficult to separate DWU by age groups since a house may hold people in several different age groups. Therefore, Spearman correlation coefficient is adopted to study the relation of DWU per household with age group. The key group will be presented with significant coefficient, which means that the corresponding group has more weight to inform the house total DWU. The result of the statistical analysis of 40 houses and 108 residents is shown in Table 2.

Table 2: Spearman correlation coefficients of DWU per house and age groups

Age groups	≤5	6~12	13~18	19~24	25~34	35~49	50~64	≥65
DWU per house	0.284	0.098	-0.187	-0.117	-0.090	0.140	0.113	0.011

* Correlation significant at the 0.05 level (two-tailed).

As seen in Table 2, no significant value is presented. The results make it clear that there is no significant correlation between DWU per home and age groups; there can be no assumption that any age group uses more water than others.

Energy use in appliances

Among the 50 houses, only four have both daily total energy consumption data and DWU data at the same time.

House No. 19 has the longest monitored days among these four houses and its energy use is also sub-metered into three separate data streams, all assumed to have direct relation with water use behavior: bathroom, clothes washer, and dish washer. Figure 8 shows the daily energy use of those three data streams and the DWU of House No. 19.

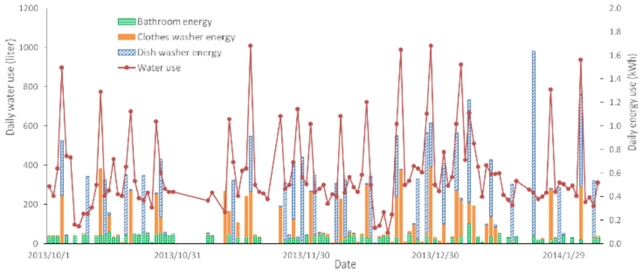

Figure 8: DWU (House No. 19) and appliances energy use

As seen from Figure 8, the bathroom shows the most constant and consistent use, at the frequency of 92 days out of a total of 116 monitoring days. While the clothes washer and dish washer are operated in 43 and 37 days, respectively, which are twice a week on average. Energy consumption in the bathroom is much less than the energy consumption of the clothes washer and dish washer, on average. This may result from the fact that light bulbs often have the power level of less than 100 W, while the dish and clothes washers have the power level of more than 2000 W. Given their different power, even if lights are turned on in the bathroom, its overall consumption is lower than that of dishwashers or washing machines. In general, the DWU has ups and downs over the monitored days; it seems higher DWU points have a corresponding higher use of energy. To test the bivariate relationship between DWU and daily energy use, linear regression is adopted. Household daily total energy use is set to be the variable at first and the result is shown in Figure 9a.

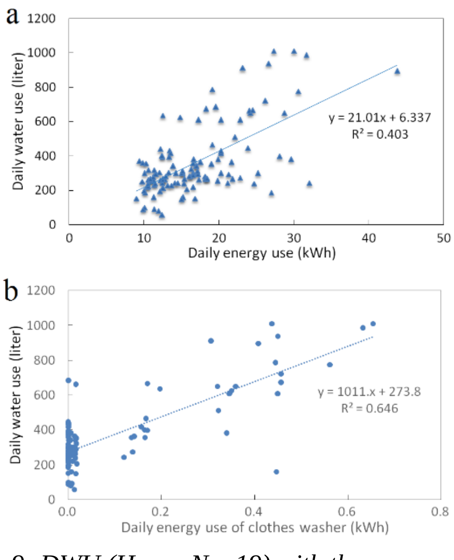

Figure 9: DWU (House No. 19) with the energy use: a) daily total energy use; b) daily energy use of clothes washer

From Figure 9a, a positive correlation is seen between DWU and daily energy use, though not a strong correlation, with an R2 value of 0.403. The disparity may come from the incomplete statistics and residents' different behaviors between water use and energy use. Therefore, the energy uses of bathroom, clothes washer, and dish washer are set to be variables separately as they have direct influence on water use. These results show that the daily energy use of the clothes washer has a better positive correlation with DWU, with R2 value of 0.646 (Figure 9b). Meanwhile, the DWU per household could not be predicted by the energy use of the bathroom as little lighting energy is used in their bathrooms.

However, not all families use dish washers or other appliances. Restricted by the sample size, this result only proves that energy use can indicate the condition of water use in residential buildings qualitatively. The most important is saving water saves energy.

Conclusions

In this case study, 95% of house median DWU values are between 90 and 650 liters per household per day, and the baseline DWU can be set as 186.00 lpcd for these houses.

Due to the limitation of the house information and no sub-metering of water use data, the current result could just show that 25% of residents consumed 51% of the total water. High water use households (or people) have potentials to significantly reduce water consumption. These results help generate awareness of water use behavior in homes and support further studies in clustering water use behavior patterns and developing water use models for simulation.

In contrast with previous research, our study found that DWU is less affected by occupancy than by residents' habits, and the resident's habits of water use is much different from those of energy use.

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