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**Hot Water Draw Patterns in Single-Family Houses:
Findings from Field Studies**

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Hot Water Draw Patterns in Single-Family Buildings

Findings from Field Studies

Abstract

This report describes data regarding hot water draw patterns that Lawrence Berkeley National Laboratory obtained from 10 studies. The report describes our purposes in collecting the data; the ways in which we managed, cleaned, and analyzed the data; and the results of our data analysis. We found that daily hot water use is highly variable both among residences and within the same residence. We also found that the distributions of daily hot water use are not symmetrical normal distributions. Thus we used median, not average, values to characterize typical daily hot water use. This report presents summary information that illustrates the results of our data collection and some initial analysis.

Introduction

Because water heating represents one of the largest energy end-uses in residential buildings, it is an important consideration in energy efficiency standards for both appliances and buildings. In residential buildings, people use heated water for showers, baths, and washing at sinks. Hot water also is used by dishwashers and clothes washers. Hot water draw patterns are a record of the timing and volume of the flow of water from a water heater. There has been a dearth of field research regarding domestic hot water systems in residential buildings. The lack of field data has meant that standards and guidelines must rely on assumptions and engineering calculations. Expanding our understanding of draw patterns supports improved system design and sizing guidelines. Other beneficial effects include the ability to calculate residential hot water use in support of energy policies and choices.

Purpose of this Study

The purpose of the project described here was to develop a database of hot water draw patterns in single-family houses based on a range of field data. Multiple recent studies have collected hot water use data from single-family residences. Although none of the studies were performed solely to evaluate hot water draw patterns, the data they collected can be used for that purpose. We collected, cleaned, and collated hot water use data from 10 independent studies. The data represent hot water flow for entire houses measured at the water heater. In some instances the data were collected from an apartment or town house unit. We used such data only if the unit had its own dedicated water heater. Because the data were collected at the water heater, we obtained no information about hot water use at fixtures or fittings.

Data Sources

One of our criteria for selecting studies was that the data must have been collected at a recording interval of 1 minute or less. Another criterion was that the source study must have been conducted after 1995. The primary field data we collected represented water flow. Some studies also recorded the temperatures of water entering and leaving the water heater. When temperature data were available, we collected those as well. Our database of field data on hot water use to date encompasses:

- 10 studies,
- 142 monitored houses,
- 200 monitored configurations of water heaters and hot water end uses,
- 27,956 days of monitoring,
- 23,994 good days (days providing acceptable data),
- 1,547,144 hot water draws, and
- 4,582,960 records of hot water use.

We expect to continue expanding and refining both the data and the analysis. Table 1 summarizes the key characteristics of the source studies examined to date.

Table 1. Characteristics of source studies

Author/Client/Code⁺	Focus of Study	No. of Houses	Duration, Date	Region, State	Recording Interval
Johnson Research, LLC, for Northeast Utilities* (NUWH)	Demand electric water heaters	2	3 months in 2003–2004	CT	1 minute
National Association of Homebuilders for Geothermal Heat Pump Corporation and National Renewable Energy Laboratory* (NAHB)	Geothermal water heating	5	17 months in 1997–1999	Cleveland, OH	1 minute
Aquacraft, Inc., for Seattle Public Utilities and U.S. EPA (AQSE)	Comparison of pre- and post-retrofit water use by end-use	Hot water data for 10 of the 37 houses studied	Typically 4 weeks of data, 2 weeks pre-retrofit and 2 weeks post-retrofit in 1999–2000	Seattle, WA	10 seconds
Aquacraft, Inc., for East Bay Municipal Utility District and U.S. EPA (AQED)	Comparison of pre- and post-retrofit water use by end-use	Data for 10 of the 33 houses	Typically 4 weeks of data, 2 weeks pre-retrofit and	East Bay, CA	10 seconds

Author/Client/Code ⁺	Focus of Study	No. of Houses	Duration, Date	Region, State	Recording Interval
		studied	2 weeks post-retrofit in 2001-2002		
Gas Technologies Institute (GTI)	Condensing water heaters	29	2 phases for most houses, 2-13 months each, in 2004-2006	Nation-wide	30 seconds
Davis Energy Group* (DAVIS)	Efficiency of hot water distribution systems	1	9 months in 2003-2004	Northern CA	2 seconds
National Renewable Energy Laboratory* (NREL)	Energy consumption of hot water systems in new energy efficient houses	2	2 months in 2009, 16 months in 2008-2009	KS and CO	1 second, 5 seconds
AIL Research, Inc., for Northeast Utilities* (NUHP)	Metered performance to estimate cost savings of heat pump water heaters	23, in 2 phases	7-10 months in 1998-1999 and 9-10 months in 1999-2000	CT and MA	1 minute
TIAX LLC for the California Energy Commission Public Interest Energy Research program* (TIAX)	Field test of prototype "market-optimized" heat pump water heater	16	3 to 20 months in 2001-2003	CA	1 minute
Natural Resources Canada (CANMET1)	Evaluation of usefulness of established regulations	38	1 to 4 weeks from August 2007-July 2008	Ottawa area	2 seconds

* Data included temperature as well as flow data.

⁺ This is the coding used to identify the study in the database.

A map showing the location of all the monitored sites is shown in Figure 1, Location of Monitored Houses. The area of each circle corresponds to the number of complete days of data for that site.

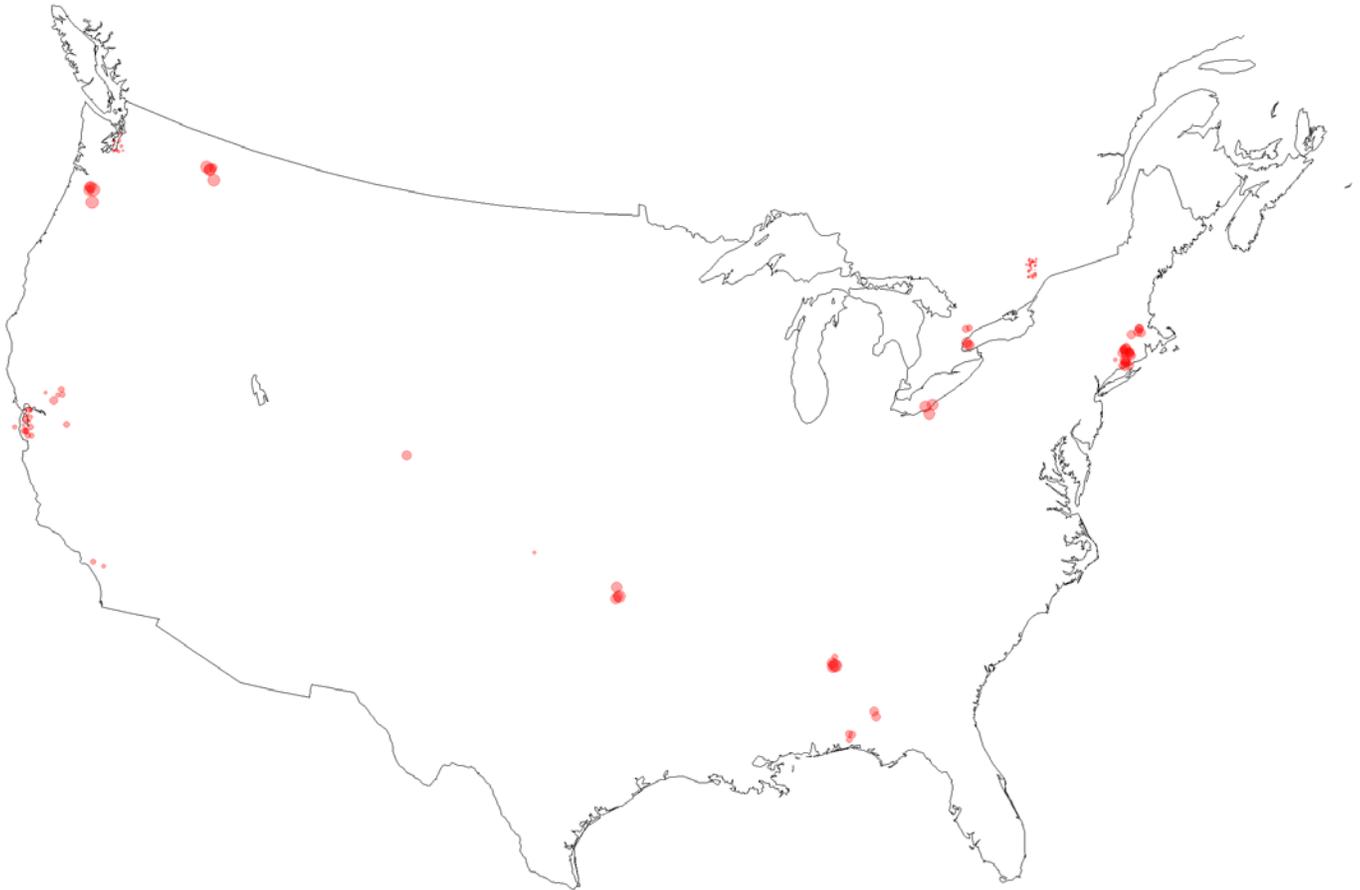


Figure 1 Location of Monitored Houses

Each of the 10 studies from which we derived data is described more fully below.

1. Northeast Utilities Demand Electric Water Heater Study^{1, 2}

In this study, two whole-house demand (also known as tankless or instantaneous) electric water heaters were monitored and compared to customers' existing gas or electric storage water heaters. The study's goal was to increase understanding of demand water heaters and to evaluate their savings potential. Each week the source of household hot water alternated between the demand heater and the storage heater. Data were collected every week throughout a 3-month test period during 2003–2004. Data were collected at 1-minute intervals. Flow and temperature data from the two monitored houses were made available for our study. This field evaluation helped

Connecticut Light and Power, an operating company of Northeast Utilities, learn about the operating characteristics of demand water heaters.

2. *National Association of Homebuilders Research Center Geothermal Water Heating Study*³

The purpose of this study was to provide potential users of geothermal water heating systems with information that would increase confidence in sizing methods and system performance. Data collection and analysis were performed on five recently built homes in the greater Cleveland, Ohio, area. The houses were monitored at 1-minute intervals for approximately 17 months in 1997–1999. Flow and temperature data for three houses were made available for our study.

3. *Seattle Home Water Conservation Study*⁴

This study was a before-and-after comparison of water use patterns from 10 single-family homes in the Seattle area. Aquacraft, Inc., performed this study to measure the impacts of various indoor water conservation fixtures and appliances on both aggregate and individual water use patterns. Acceptance of the water conserving fixtures and appliances also was evaluated. The 10 houses were monitored for periods ranging from 2 to 8 weeks in 1999–2000. Data were recorded every 10 seconds. Flow data from all 10 houses were made available for our study. The study was funded by a grant from the U.S. Environmental Protection Agency (EPA).

4. *East Bay Municipal Utility District Indoor Residential Water Conservation Study*⁵

This study evaluated the impacts and acceptance of high-quality water conservation fixtures and appliances in single-family homes in the East Bay area of California. This study, performed by Aquacraft, involved a before-and-after comparison of water use patterns from 33 single-family homes in the district's service area. Hot water use was recorded for 10 of the 33 houses for 6 to 8 weeks in 2001. Flow data from all 10 houses were made available for our study. The East Bay Municipal Utility District and the U.S. EPA funded the study.

5. *Gas Technologies Institute Condensing Water Heater Field Study*

The institute performed this field study of a market-optimized condensing gas water heater for residential applications. The product was tested in various types of homes throughout the United States. The project involved metering water flow for 29 houses at 30-second intervals.

6. *Davis Energy Group Water Heater Field Study*⁶

In this study, hot water usage was monitored for one house in northern California to better understand factors that affect the energy efficiency of hot water distribution systems. Data were collected at 2-second intervals for 9 months in 2003 and 2004.

7. *National Renewable Energy Laboratory*

This study involved testing and monitoring the energy consumption of hot water systems in two newly built energy efficient houses in Kansas and Colorado. Data were collected every 1 second or 5 seconds for a total of 18 months in 2008-2009.

8. *Northeast Utilities Heat Pump Field Study*⁷

We utilized data from a field study performed to determine the efficiency and cost savings of newly installed heat pump water heaters in 30 houses. Two sets of field measurements collected over 9 months each in 1998–2000. The goal was to predict cost savings compared to electric resistance water heaters.

9. *TIAX Heat Pump Water Heater Study*^{8, 9}

TIAX field-tested a new “market-optimized” heat pump water heater. The project was intended to refine the design of a prototype product through both laboratory and field testing. This study provided supplemental information to the final report for a previous project in which two generations of prototype market-optimized heat pump water heaters were developed and tested. In this 2002–2003 field study of a third-generation prototype, conducted in 20 California homes, data were recorded every minute. Monitoring periods ranged from 6 to 27 months. Flow and temperature data for 16 residential sites were made available for our study. The Public Interest Energy Research program, managed by the California Energy Commission, funded this study.

10. *Natural Resources Canada*^{10, 11}

Natural Resources Canada performed field testing to determine whether current regulations and standards regarding residential hot water heaters are still relevant and appropriate for today’s new technologies. The study measured flow rate and number, durations, and volume of hot water draws at 40 sites, each monitored for 2–4 weeks.

Data Processing

We maintained the original data and reports from each study together in their original structure. The 10 studies provided huge quantities of data that were impossible to analyze by hand or with spreadsheets. We used software scripts written in perl,¹ a multipurpose programming language, to automate the process, reduce errors, and provide for a consistent analysis. The scripts also enabled us to re-run computations easily to include refinements and corrections. Figure 2 presents a flow chart of the data processing operations whereby raw data were cleaned, processed, and summarized. After the data were processed, we imported it into a database. We expect to continue adding to and refining the database as more resources come available.

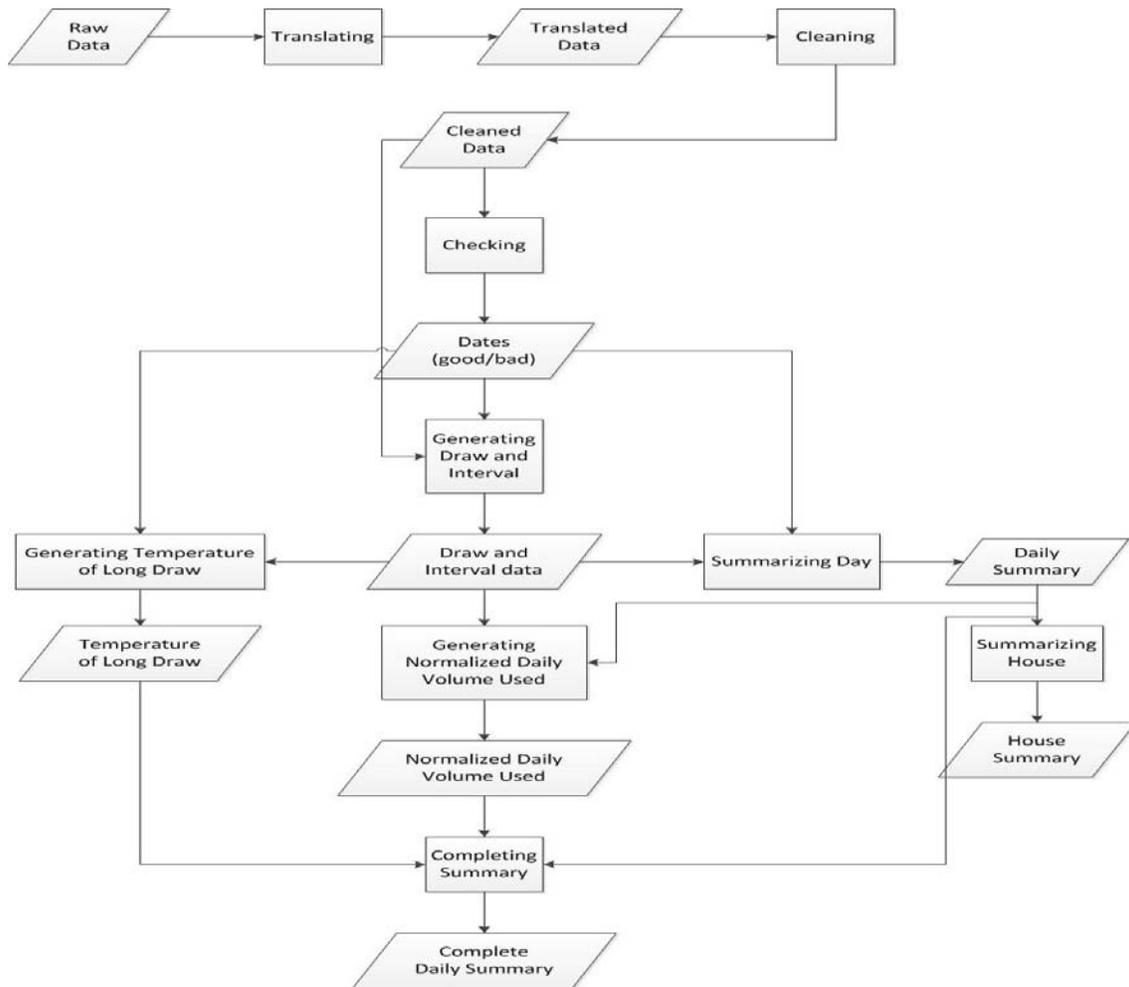


Figure 2. Flowchart of data and programs

The steps we took to process the data are described below.

1. *Translating*

¹ The Perl Programming Language, <http://www.perl.org/>.

Data from the various studies were supplied in different file formats (spreadsheets, databases, proprietary binary files, ASCII text files, etc.). The first step was to translate all the data from all studies into a consistent comma-separated values format. We created macros, software, scripts, and so on to translate the data. All the translated data files were further processed in the following steps.

2. *Cleaning*

The second step was to clean all the translated data derived from step 1 above. Cleaning meant keeping only selected fields, changing the date and time format, converting units of measure (if needed), combining all the data from the same house into one file, and removing duplicate records. We created perl scripts to clean the translated data files for each study.

3. *Checking*

After completing the translating and cleaning steps, we performed an automated quality assurance check on the data. We had records for 27,956 days for all houses in the database. Of those, 23,991 days passed the checking criteria for inclusion in the SUMMARY_DAY table.

Because hot water use shows daily cycles, we included a day only if we had a complete set of good data for that day. Otherwise, it was classified as a “bad” day and excluded. The DATES table includes a record for all 27,956 days for which we had data. Excluded days are noted as “bad,” and the reason they were excluded is listed.

We had two broad criteria for checking the quality of data for a day: whether the data were complete and whether they were good.

The completeness criterion was applied to avoid using data from incomplete days. However, we did not want to exclude days when the occupants used no hot water but the data were complete. We applied the completeness criterion to studies that recorded data continuously. For those data sets, no more than 30 minutes total and no more than 10 continuous minutes of data could be missing during a day.

Two studies recorded data when hot water was flowing and once every 15 minutes even if water was not flowing. If more than two 15-minute “heartbeat” records were missing, equivalent to missing 30 minutes of data, we excluded that day.

Some of the studies recorded data only when water was flowing. For those studies, we excluded the last day of the monitoring period and the first day of the monitoring period if the data recording started after noon.

Regarding the second broad criterion, if some of the data for a day were implausible, we excluded the entire day on the assumption that something was wrong with the data collection system that day. The water flow rates had to be between 0 and 20 gallons per minute. For studies in which water temperatures were recorded, all inlet and outlet water temperatures had to be between freezing and boiling. In addition, the highest incoming

cold water temperature for any day had to be less than the highest outgoing hot water temperature for the same day.

We also visually examined some data sets for which the summary data exhibited suspicious patterns. Based on this examination, we manually removed certain days for certain houses from the data set. For example, we removed every day before 7/15/1999 from house NUHP_224. The highest and lowest inlet temperatures on those days were 10 to 20 degrees above those for all the other days for that house. We also removed several weeks of data from NUHP_218 and GTI_ALA-2_Phase-1, because the pattern of draws and water use was abnormal compared to the other days recorded at the same houses.

4. Generating Draw and Interval Data

After checking the data, we used perl scripts to generate draw and interval data for good days. The resulting data set contains the measured volume of hot water for each time interval when water flow was detected for every household in every study that provided useable data. We also included the cold (inlet) and hot (outlet) water temperatures when available.

For this analysis we considered a draw to be a period of uninterrupted flow of water through the water heater. When the flow stopped for at least one data-recording interval, we considered that draw to have ended. This definition means that overlapping draws made for different uses were counted as one draw. It also means that if two draws were separated by an interval shorter than the data-recording interval, we considered them as one draw.

We recorded the starting time and the duration for each draw. We did not correct the start time and duration for flows that occurred for only a part of a monitoring interval, because there was no way to know from the data when this had happened. For each draw we calculated the time elapsed since the previous draw. We also calculated and recorded the total volume of each draw.

After taking the above steps, we moved on to the following steps.

5. Summarizing Days

Using draw and interval data from good days only, we summarized the hot water usage for every house. The summaries include, for example, the total number of draws and total gallons of hot water used each day for each house.

6. *Summarizing Houses*

Using the data from all daily summaries, we summarized the hot water use for each particular house.

7. *Determining Temperatures During Long Draws*

In this step, we generated the average inlet and outlet temperatures for draws that lasted at least 4 minutes. We used only the temperature after 1 minute. If a draw lasted 5 minutes, for example, only the temperature records from minutes 2 to 5 were used; temperature records from minutes 0 to 1 were ignored. We ignored the first minute to get a measurement of the temperature of the hot and cold water after any local heat transfer or thermosiphon effects during standby had been cleared from the water lines.

8. *Calculating Normalized Median Daily Hot Water Use and Draws*

Data from daily summaries enabled us to generate a normalized median value of daily hot water use for each house by dividing each day's hot water use by the median daily hot water used for that house. We also generated a normalized median value for the number of hot water draws per day.

DATABASE

The processed and aggregated data from the studies were incorporated into a database for further analysis. The database consists of six tables, which are described briefly below. A full description, including an explanation of the fields of each table in the database, is provided in Appendix A.

Houses

The HOUSES table contains information about the houses that were monitored. The records for this table comprise 65 fields that include information such as the number of people living in the house, the location of the house, and the time interval at which data were collected.

Unfortunately this table is very sparse. Each study collected different data about the houses they monitored. Data in many of the fields were only available from one or a few studies.

Several of the studies collected data from the same house under different configurations. An example of this is Aquacraft's Seattle study, which measured water use before and after installing water efficiency measures such as low-flow showerheads and water efficient dishwashers and clothes washers. The building and the people occupying the house remained the same, but the water heater and/or the hot water end uses changed. For most analyses we considered houses under different phases of a

study to be different house configurations, and assigned them different house_ids. The database has data from 142 houses. The HOUSES table has 200 house_id records.

Dates

The DATES table contains a record for all 27,956 house days for which we have data. This table lists whether we considered the data for that day “good” or “bad” and the reason a day was designated bad.

Intervals

This table contains the water flow and, when available, temperature data for every recorded interval on good days only from the monitored houses. It contains 4,582,960 records, but only 8 fields.

Draws

This table contains the aggregated data for every draw that occurred on good days. We used the interval data to determine the draws before they were imported into the database.

Summary Day

The records in this table contain the aggregated information about each of the 23,994 “good” house-days in the database.

Summary House

This table contains the summary information about hot water use for each house_id.

Results

Based on the hot water draw patterns for the 23,994 good days from the 200 configurations of water heaters and hot water end uses in houses (from 142 monitored homes), we determined the daily volume of hot water use and the daily number of draws. The results include the volume of hot water used and the number of draws per day by the number of occupants in single-family residences.

One distinctive feature of daily hot water use is its variability. A simple, unweighted calculation of the average hot water use for all households and all days in our database gives 58.7 gallons per day (GPD), with a standard deviation of 38.8 GPD. There is also a large variation in use from day to day within one house. See figure 3 for an example of the variation of daily hot water use.

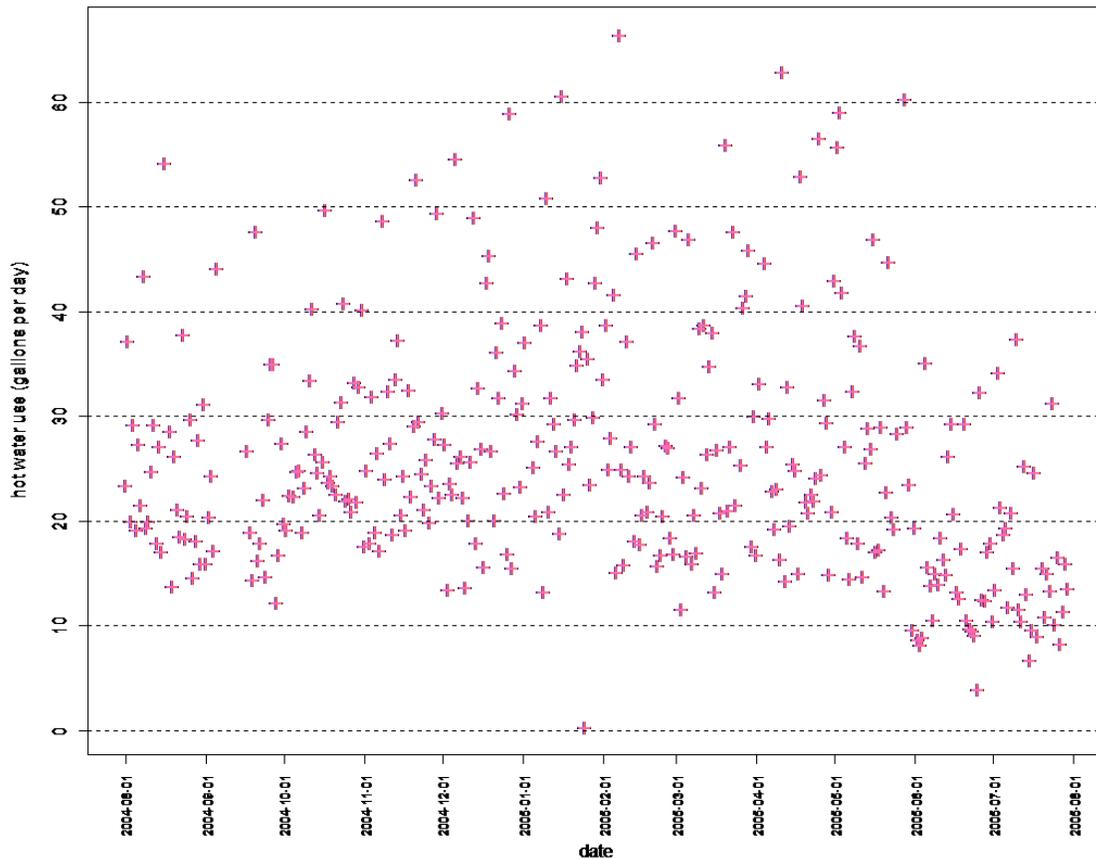


Figure 3 Daily Hot Water Use (house_id = GTI_OKL-1_Phase-1)

Any algorithm applied to model daily hot water use clearly requires a large stochastic or random component.

Another striking feature of the data is that the distributions of daily hot water use are not symmetrical normal distributions. There are a few days when hot water use is much greater than the average, and, of course, days when hardly any hot water is used. This feature could be captured by modeling the random component of daily hot water use in two parts. The primary distribution can be represented as a log-normal distribution. Because a log-normal distribution does not include zero, a second part of the random component would capture the occurrence of days when no hot water is used.

Figure 4 shows the distributions of hot water use in 1 gallon per day bins. The long tails of these distributions, which are characteristic of log-normals, mean that medians are better descriptors than averages.¹²

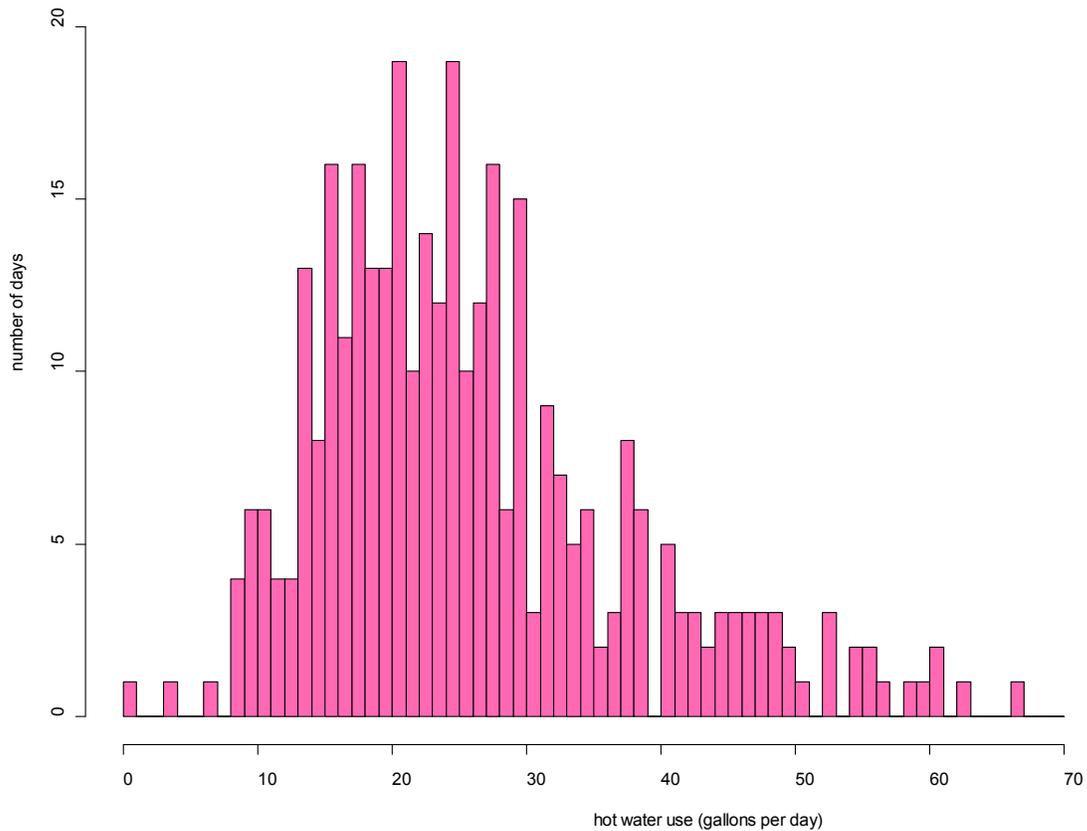


Figure 4 Frequency of Daily Hot Water Use (house_id = GTI_OKL-1_Phase-1)

Daily Volume of Hot Water Use

One way to compare the variation of use between different houses is to examine median daily hot water use. The average daily median volume of hot water use among our sample of houses is 50.6 gallons. Figure 5 shows a cumulative distribution of median daily hot water use. For most houses the median use of hot water is between 20 and 80 gallons per day.

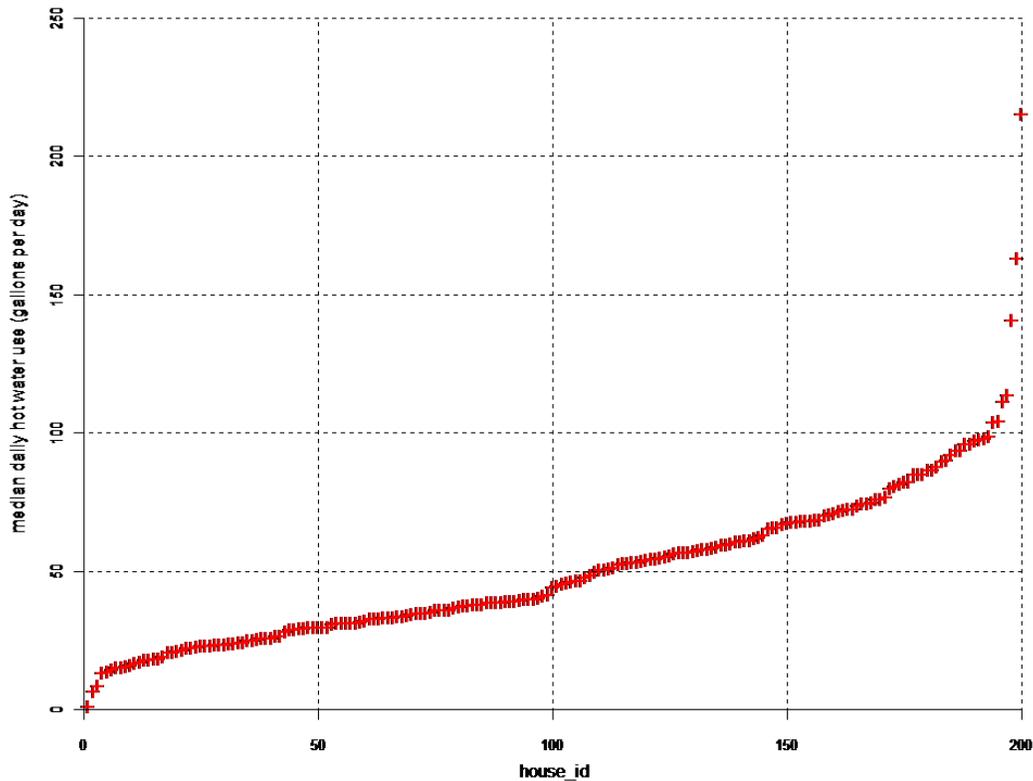


Figure 5 Median Daily Hot Water Use by Configuration of Water Heater and Hot Water End Uses

Median daily hot water use correlates strongly, but not linearly, with the number of people in a household. As Figure 6 shows, however, there is a wide range of median daily hot water use among households that have the same number of occupants. Each box plot shows the distribution of median daily hot water use by houses with the same number of occupants. The horizontal bar is the average daily median hot water use for houses with that number of occupants. The solid region shows the range of the upper and lower quartiles. The whiskers are within two standard deviations. Outliers are indicated by dots. The width of each box corresponds to the number of houses represented, also listed as the number above the center box.

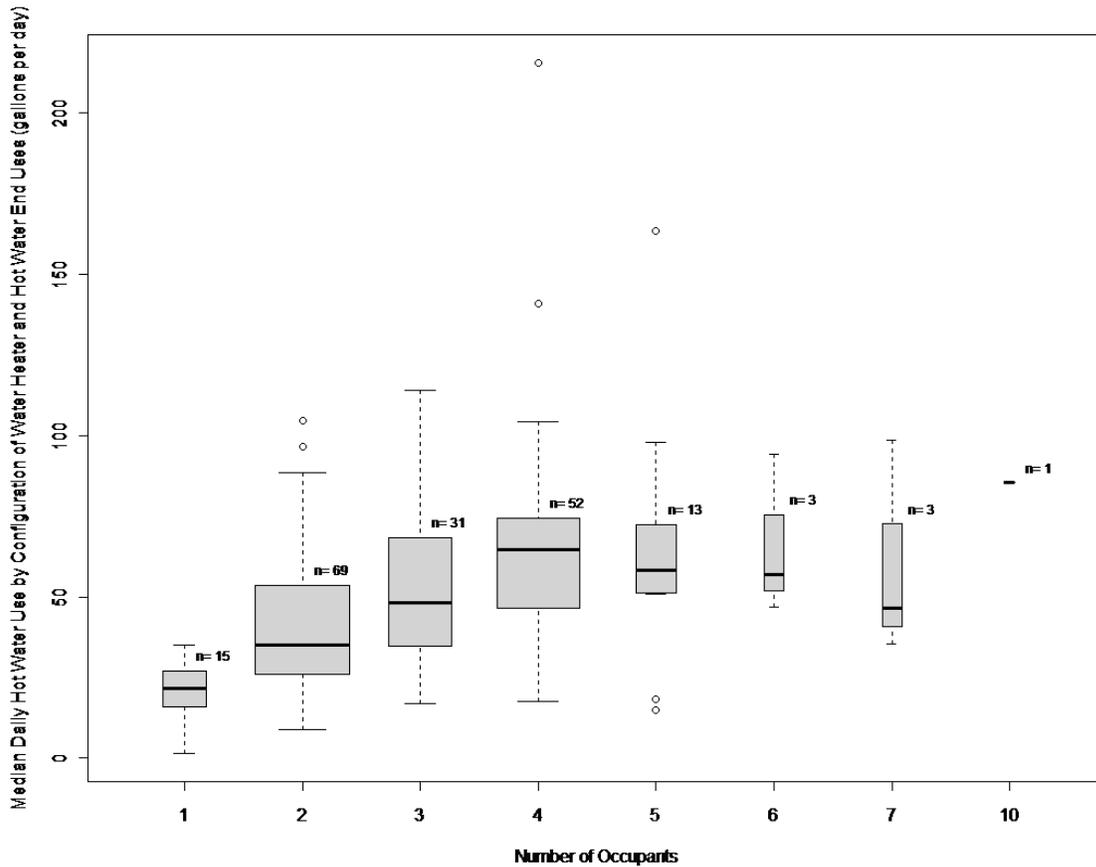


Figure 6 Median Daily Hot Water Use by Number of Occupants

Factors that may be responsible for the variations in use among similar-sized houses beyond the number of occupants, include the presence of hot water-using fixtures or appliances (for instance spa tubs), temperature of the inlet water, ages of the people in the household, and variations in water use habits. Other factors may influence median daily hot water use as well. Because such parameters were not recorded consistently in the monitoring studies that provided data, it was beyond the scope of this project to analyze those factors.

Number of Draws per Day

The average daily median number of hot water draws among the sample households is 61.6. The median number of draws for most households ranged between 25 and 100 draws per day.

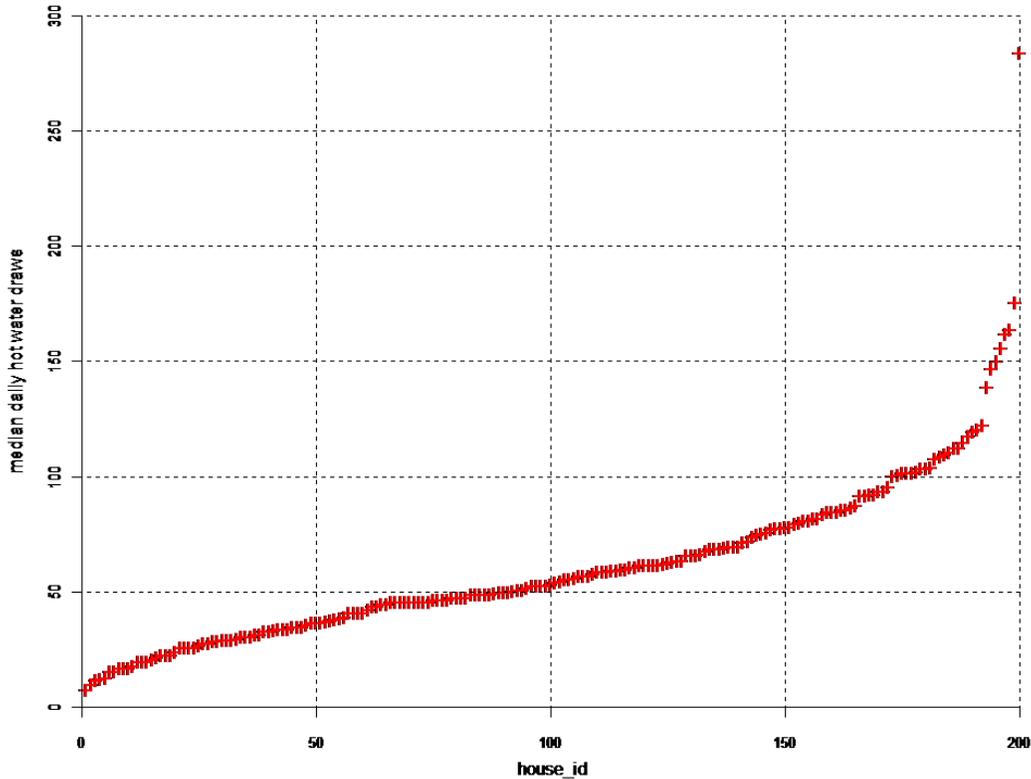


Figure 7 Median Daily Hot Water Draws by by Configuration of Water Heater and Hot Water End Uses

The median daily number of hot water draws roughly correlates with the number of residents in a house. Figure 8 shows, however, that there is a wide range of median number of hot water draws among houses that have the same number of occupants.

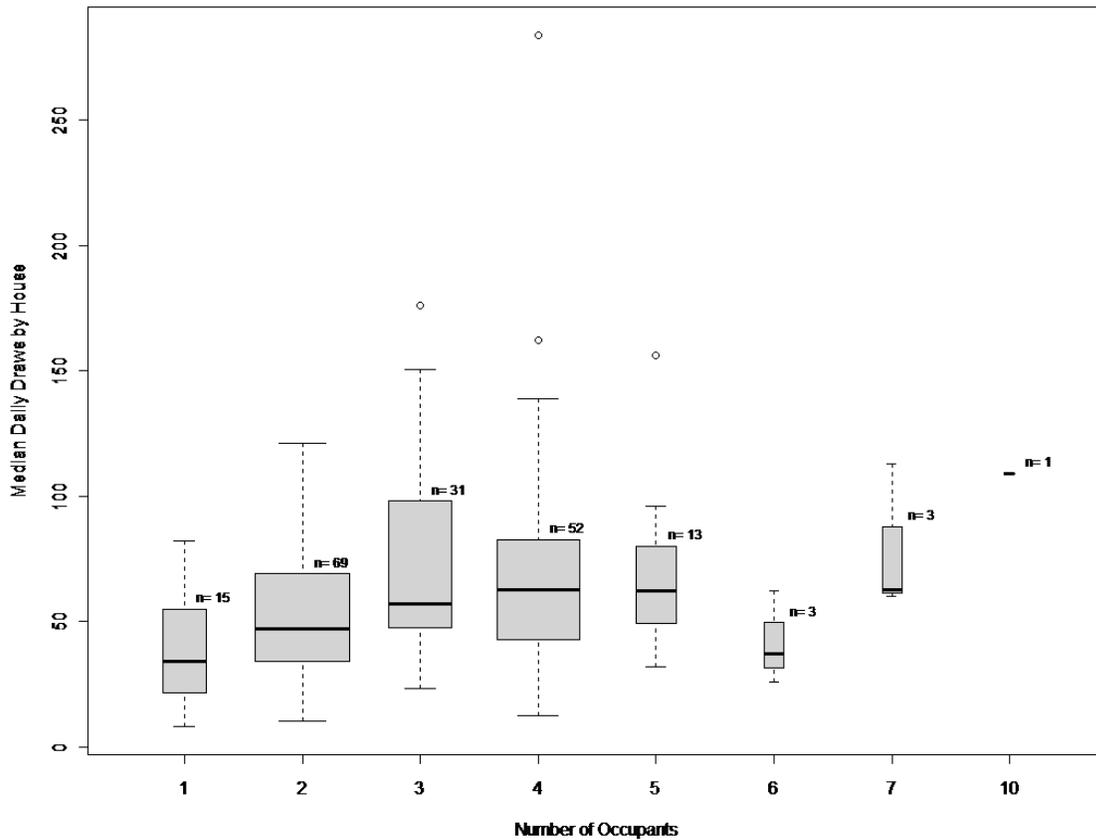


Figure 8 Median number of daily hot water draws by number of occupants

An extra confounding variable for some of the variation in median daily number of hot water is the length of the data recording interval. As mentioned earlier longer recording intervals may be masking some number of draws.

Hot Water Volume and Draws

Figure 9 shows the median daily number of draws by the median volume of hot water use. Each symbol represents one configuration of water heater and hot water end uses in a house. The color of the symbol represents the duration of the recording interval. The size of the circles corresponds to the number of days of monitoring. There is some correlation across house configurations between the daily number of draws and the daily volume of hot water used. Also the number of draws per day tends to increase with shorter recording intervals. This is expected as larger recording intervals would tend to aggregate draws that happen to nearly overlap.

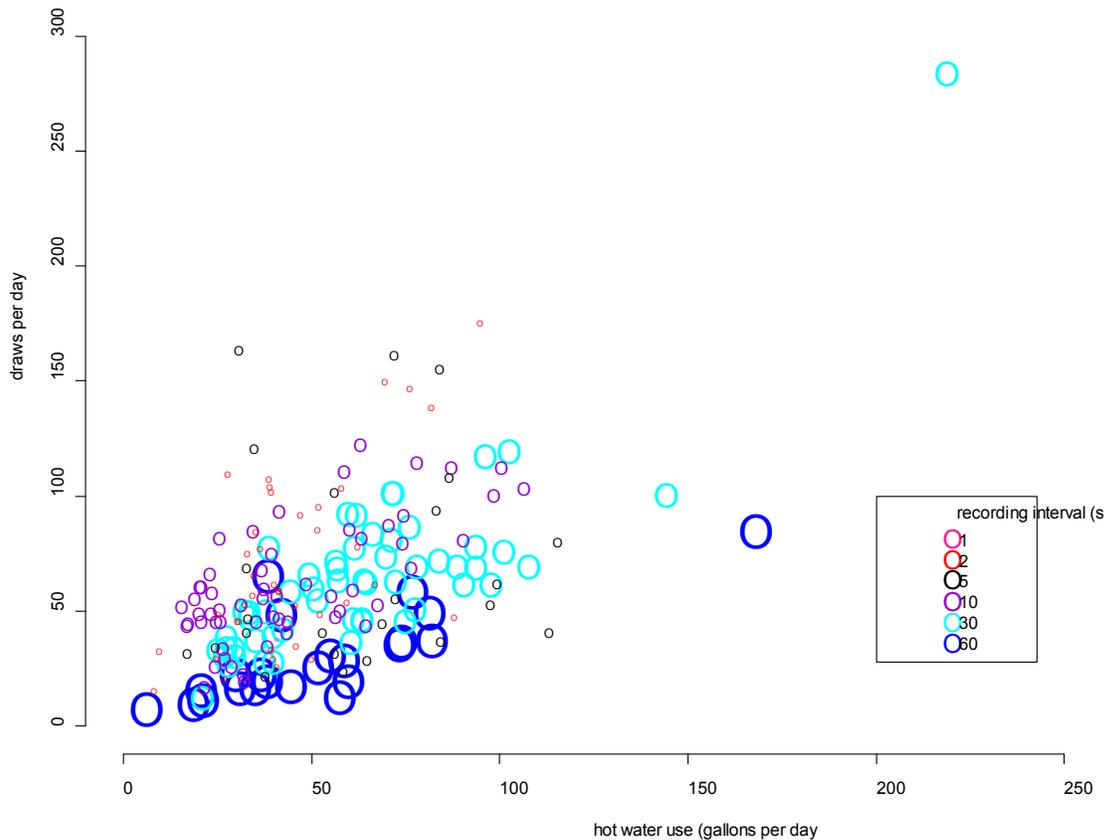


Figure 9 Daily Number Draws by Daily Volume

Conclusions and Recommendations

A distinctive feature of daily hot water use, confirmed by this study, is its variability. Another striking feature is that the distributions of daily hot water use are not symmetrical normal distributions. The distributions have long tails, which is why we used medians, not averages, to characterize typical daily hot water use. An asymmetrical distribution, such as a log-normal, would be a much better descriptor than a normal distribution.

Our study found a high number of draws per day, up to 180. For most houses the median daily number of draws ranges from 20 to 120.

The number of draws has particular impact on the start-up losses from tankless water heaters and the losses in hot water distribution systems. These results indicate the need for further study of hot water draw patterns.

Nearly all of the analyzed houses used a storage water heater. Without including additional studies, the information in the database cannot be used to determine whether households with tankless water heaters use more or less hot water than households which have storage water heaters, although this topic warrants additional investigation.

The studies from which we derived our data did not identify the configurations of the distribution systems in the houses that were monitored. This data set does not support a determination of whether distribution systems of different configurations lead to different hot water draw patterns. This topic also warrants further investigation.

Clearly much more work is necessary to understand residential hot water draw patterns. We hope to expand the data set and continue with these analyses to further the understanding of residential hot water draw patterns.

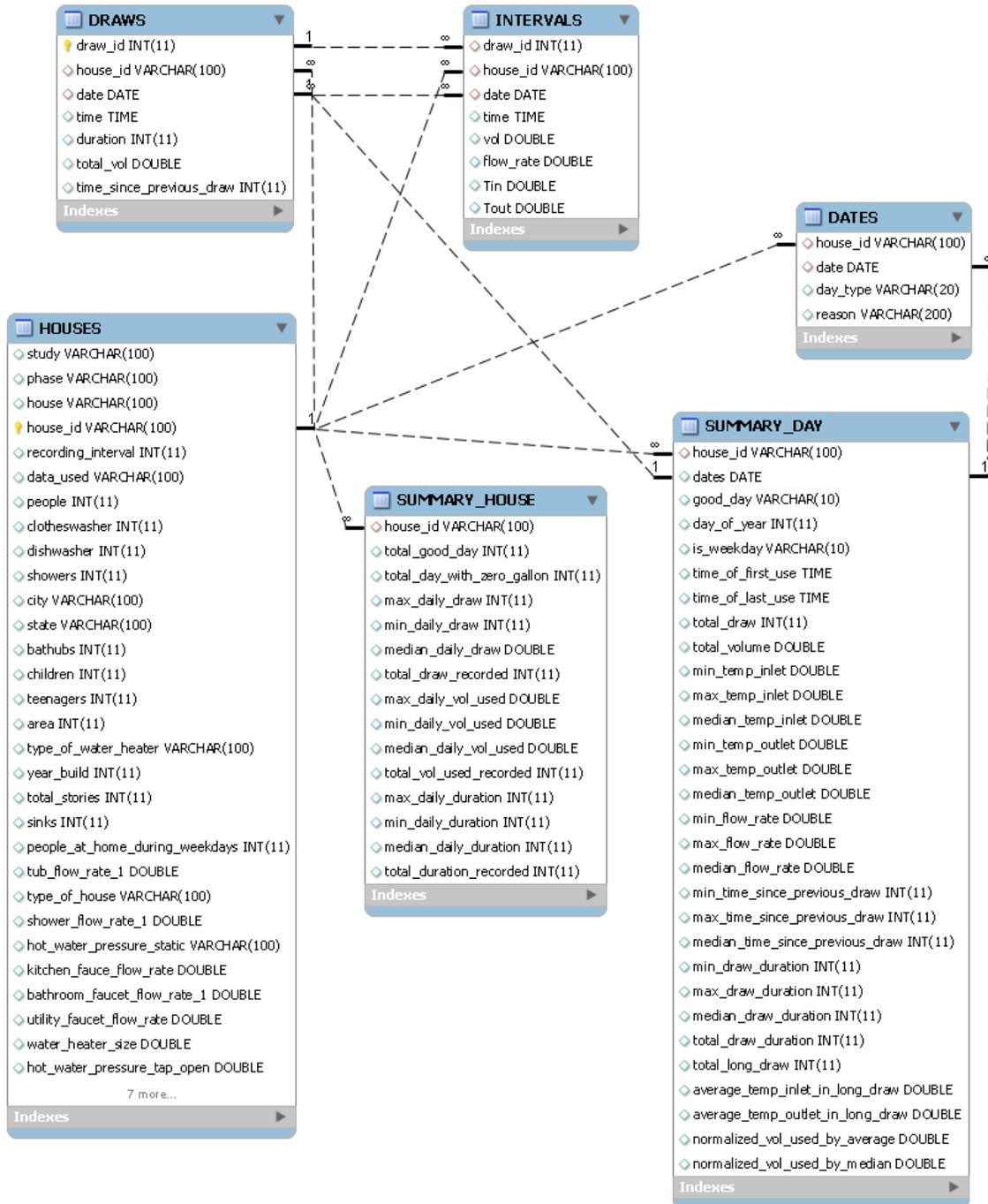
References

-
- 1 Johnson Research, LLC. A Field Evaluation of Two Demand Electric Water Heaters for Northeast Utilities. Performed by Johnson Research, LLC, Glastonbury, CT, for Northeast Utilities. April 2, 2004.
 - 2 Johnson, R.K., and C.A. Craig. Field Evaluation of Two Demand Electric Water Heaters for Northeast Utilities. Presented at the 2006 annual meeting of the American Society for Heating, Refrigerating and Air-Conditioning Engineers, Chicago IL, January 21-25 2006. ASHRAE Transactions, vol. 112 (2), pp. 426-435.
 - 3 National Association of Home Builders (NAHB) Research Center. Measured Performance of Five Residential Geothermal Systems. Performed by NAHB, Upper Marlboro, MD, for the Geothermal Heat Pump Consortium National and the National Renewable Energy Laboratory. November 22, 1999.
 - 4 Mayer, P.W., W.B. DeOreo, and D.M. Lewis. Seattle Home Water Conservation Study: The Impacts of High-Efficiency Plumbing Fixture Retrofits in Single-Family Homes. Performed by Aquacraft, Inc., Water Engineering and Management, Boulder, CO, for Seattle Public Utilities and the U.S. Environmental Protection Agency. December 2000.

-
- 5 Mayer, P.W., W.B. DeOreo, E. Towler, and D.M. Lewis. Residential Indoor Water Conservation Study: Evaluation of High-Efficiency Indoor Plumbing Fixture Retrofits in Single-Family Homes in the East Bay Municipal Utility District Service Area. Performed by Aquacraft, Inc., Water Engineering and Management, Boulder, CO, for East Bay Municipal Utility District and the U.S. Environmental Protection Agency. July 2003.
 - 6 Davis Energy Group, Inc. Progress Report on Building America Residential Water Heating Research. Draft report prepared by Davis Energy Group, Inc., for Steven Winter Associates. November 14, 2003.
 - 7 ALL Research, Inc., and R.K. Johnson. Heat Pump Water Heater Field Test: 30 Crispaire Installations. Final report prepared by ALL Research, Inc., Princeton, NJ, for Northeast Utilities. April 4, 2001.
 - 8 TIAX LLC. Design Refinement and Demonstration of a Market-Optimized Heat-Pump Water Heater. Prepared by TIAX LLC, Cambridge, MA, for the California Energy Commission Public Interest Energy Research Program under Contract No. 500-98-028. April 2004.
 - 9 TIAX LLC. California Field-Test Data and Analysis. Attachment to the final report prepared by TIAX LLC, Cambridge, MA, for the California Energy Commission Public Interest Energy Research Program under Contract No. 500-98-028. April 2004.
 - 10 Thomas, M., A.C.S. Hayden, K. Wittich, and D. MacKenzie. Residential Hot Water Use and its Implications for Gas-Fired Water Heater Efficiency and Future Canadian Performance Test Standards. Presented at the International Gas Union Research Conference, Paris, 2008.
 - 11 Thomas, M., S. Hayden, K. Wittich, and D. MacKenzie. Hot Water Use Field Test Results. Slide presentation made at Camsell Hall, August 25, 2008, by the Integrated Energy Systems Laboratory, CANMET Energy Technology Centre, Natural Resources Canada. 35 slides.
 - 12 Limpert, E., W. A. Stahel, and M. Abbt. Log-normal Distributions across the Sciences: Keys and Clues. *BioScience*, vol. 51, p. 12, May 2001.
<stat.ethz.ch/~stahel/lognormal/bioscience.pdf>

Appendix A – Hot Water Draw Patterns Database Structure and Fields.

The relationship among the tables in the database are shown in the following figure. Each table in the database is described on subsequent pages.



HOUSES

The HOUSES table contains 200 records. There is one record for every house_id. house_id is a combination of house, study, and phase. The table has 37 fields. The fields and variable type are listed below.

Field	Type
study	varchar(100)
phase	varchar(100)
house	varchar(100)
house_id	varchar(100)
recording_interval	int(11)
data_used	varchar(100)
people	int(11)
clotheswasher	int(11)
dishwasher	int(11)
showers	int(11)
city	varchar(100)
state	varchar(100)
bathubs	int(11)
children	int(11)
teenagers	int(11)
area	int(11)
type_of_water_heater	varchar(100)
year_build	int(11)
total_stories	int(11)
sinks	int(11)
people_at_home_during_weekdays	int(11)
tub_flow_rate_1	double
type_of_house	varchar(100)
shower_flow_rate_1	double
hot_water_pressure_static	varchar(100)
kitchen_faucet_flow_rate	double
bathroom_faucet_flow_rate_1	double
utility_faucet_flow_rate	double
water_heater_size	double
hot_water_pressure_tap_open	double
bathroom_faucet_flow_rate_2	double
shower_flow_rate_2	double
tub_flow_rate_2	double
location_of_water_heater	varchar(100)
shower_flow_rate_3	double
bathroom_faucet_flow_rate_3	double
foundation_type	varchar(100)

INTERVALS

The INTERVALS table contains information for all interval data from all good days for all houses. It has 4,582,960 records and 8 fields. The fields and variable type for each field are listed below.

Field	Type
draw_id	int(11)
house_id	varchar(100)
date	date
time	time
vol	double
flow_rate	double
Tin	double
Tout	double

DRAWS

The DRAWS table contains information for all draws for all good days for all houses. Draws are defined as contiguous recording intervals with water flow. The table has 1,547,144 records and 7 fields. The fields and variable type for each field are listed below.

Field	Type
draw_id	int(11)
house_id	varchar(100)
date	date
time	time
duration	int(11)
total_vol	double
time_since_previous_draw	int(11)

DATES

The DATES table contains information for all days for all houses in the studies. Each record refers to one day. Whether the day has been classified as ‘good’ or ‘bad’ is listed in the ‘day_type’ field. The reason a day was classified as ‘bad’ is listed in the ‘reason’ field. The table has 27,956 records, one for each day, and 4 fields. The fields and variable type for each field are listed below.

Field	Type
house_id	varchar(100)
date	date
day_type	varchar(20)
reason	varchar(200)

SUMMARY_DAY

The SUMMARY_DAY table contains summary information about hot water use for all good days for all houses. It has 23,991 records, one for each good day. The 30 fields and variable type for each field are listed below.

Field	Type
house_id	varchar(100)
dates	date
good_day	varchar(10)
day_of_year	int(11)
is_weekday	varchar(10)
time_of_first_use	time
time_of_last_use	time
total_draw	int(11)
total_volume	double
min_temp_inlet	double
max_temp_inlet	double
median_temp_inlet	double
min_temp_outlet	double
max_temp_outlet	double
median_temp_outlet	double
min_flow_rate	double
max_flow_rate	double
median_flow_rate	double
min_time_since_previous_draw	int(11)
max_time_since_previous_draw	int(11)
median_time_since_previous_draw	int(11)
min_draw_duration	int(11)
max_draw_duration	int(11)
median_draw_duration	int(11)
total_draw_duration	int(11)
total_long_draw	int(11)
average_temp_inlet_in_long_draw	double
average_temp_outlet_in_long_draw	double
normalized_vol_used_by_average	double
normalized_vol_used_by_median	double

SUMMARY_HOUSE

The SUMMARY_HOUSE table contains summary information for hot water use for all good days for all houses. It has 200 records, one for each house_id. The 15 fields and variable type for each field are listed below.

Field	Type
house_id	varchar(100)
total_good_day	int(11)
total_day_with_zero_gallon	int(11)
max_daily_draw	int(11)
min_daily_draw	int(11)
median_daily_draw	double
total_draw_recorded	int(11)
max_daily_vol_used	double
min_daily_vol_used	double
median_daily_vol_used	double
total_vol_used_recorded	int(11)
max_daily_duration	int(11)
min_daily_duration	int(11)
median_daily_duration	int(11)
total_duration_recorded	int(11)