

Environmental Science: Water Research and Technology

Supporting Information for

**Disaggregating Residential Sector High-Resolution Smart Water Meter Data into
Appliance End-Uses with Unsupervised Machine Learning**

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Introduction

During the initial smart water meter installation, we conducted a water audit with one of the home occupants, using the form shown in Figure SI1. This data collection included only factual data such that this work was determined not to meet the definition of human subjects research and, therefore, did not require Institutional Review Board (IRB) approval. Documentation of this IRB decision is available upon request.

Residential Water Use Survey

Date: _____
 Researcher: _____
 Address: _____

ID CODE: _____

Household Information

Number of Occupants: _____
 Age of Occupants: _____ Adults (18+) _____ Teenagers (13-17) _____ Children (under 13)
 Sq. Footage of Home: _____
 Lot Size: _____
 Year Home Built/Approx. Age: _____
 Rent/Own: _____
 Approx. Market Value: _____
 Water Heater Energy Source (Circle): Electricity Natural Gas Propane Other _____
 Are there any known leaks or dripping taps in the home? Where? _____

Type of Residence

_____ Single Family _____ Town House
 _____ Apartment Complex _____ Mobile Home
 _____ Duplex/Triples _____ Other (please specify) _____

Can the researcher take photos of the fixtures/appliances?

☐ Yes ☐ No

END-USES		COUNT	BRAND/YEAR	MODEL NO.	NOTES (Tank or Flush Style; 1.6/1.28 gpf; Dual Flush; Low Flow Shower Head; Pipe Sizing; Meter Size; Location)
KITCHEN	Dishwasher				
	Ice Maker				
	Kitchen Sink				
BATHROOM	Toilet				
	Bathtub w/ Shower				
	Bathtub Only				
	Shower Only				
	Tub w/ Jets				
	Bathroom Sink				
UTILITY	Top Load C. Washer				
	Front Load C. Washer				
	Utility Sink				
OUTDOOR	Swimming Pool				
	Hot Tub				
	Irrigation System		--	--	
	Hose Bib				
OTHER	Water Powered Sump				
	Humidifier				
	Water Softener				
	Reverse Osmosis				
	Other				
	Other				

Figure SI1. Blank water audit form to document appliances/fixtures in the study home.

We compared the results of the k -means clustering disaggregation algorithm with measured training data from the test home and the reported manufacturers' ratings for appliances/fixtures. This comparison is reported in Table SI1.

k -means clustering is an unsupervised machine learning method that is used to classify data through a predetermined number of clusters. The k -means algorithm minimizes the objective function known as a squared error function, as shown in Equation SI1.

$$J(V) = \sum_{i=1}^C \sum_{j=1}^{C_i} (\|x_i - v_i\|)^2 \quad \text{Equation SI1}$$

where x_i is a data point, v_i is a center, $\|x_i - v_i\|$ is the Euclidean distance between x_i and v_i , C_i is the number of data points in the i^{th} cluster, C is the number of cluster centers.

Comparing the measured values for the end uses throughout the home to the manufacturers' ratings can support further analyses of the actual function of the end uses. Previous studies that compared actual measurements to manufacturers' ratings did not go in depth into all appliances nor have they been on a large scale. Mead and Aravinthan (2009) examined 10 households with smart water meters and compared the water use to manufacturers' estimates at the time, although not the specific models installed in the households. However, most of the discrepancies between the measured water consumption and the manufacturers' estimates were attributed to human behaviors (such as holding down a toilet flush lever too long) or errors in data disaggregation (such as humans using a faucet immediately after using a fixture like a toilet). A more extensive comparison of exact models installed within homes surveyed has not been examined before, to our knowledge.

In addition to analyzing how the existing appliances/fixtures in the home performed compared to their ratings, these appliances/fixtures were also compared to others currently available on the market. These findings are displayed in Tables SI2 and SI3. *Consumer Reports* ratings were used for the year 2018 to find the top fixtures and appliances sold to the public in the United States, as ratings for 2019 were not yet available when conducting the study (Consumer Reports, 2018b, 2018a, 2018c). The 15 highest-rated appliances/fixtures in each end-use category were investigated to determine water use, most commonly from online appliance/fixture manuals. Most appliance/fixture manuals had the water use listed; however, for some, like many of the washing machines, the water use was not in the manual and we located through the Energy Star website.

Washing machine manuals often reported the integrated water factor more than the total water use, yet integrated water factors were also not reported for several washing machine models. For the faucets and showers, there were no *Consumer Reports* ratings, so top manufacturers were selected by searching popular brands at major U.S. department stores and analyzing consumer reports articles on various manufacturers. These data were used to compare to the appliances installed at the study home, as well as to Energy Star and WaterSense criteria reported by the U.S. Environmental Protection Agency. Energy Star ratings applied to washing machines and dishwashers, while WaterSense rates some fixtures, such as toilets and faucets. WaterSense only rates washing machines and dishwashers on a household scale, not by individual appliance. Many of the top-rated appliances/fixtures from *Consumer Reports*, shown in Tables SI2 and SI3, were from the same companies. However, this level of popularity does not necessarily reflect what the general public has widely installed in homes. Furthermore, almost all of the

dishwashers and washing machines listed were Energy Star certified as this label has become a more common and desirable rating in recent years (Ward et al., 2011).

Table SI1: The disaggregated water meter data were reasonably aligned with the manufacturers' ratings.

End-Use	Make/Model	Manufacturer's Rating* (vol/max flow)	Training Data (vol/max flow)	Disaggregated Data Coherence (flow)	Disaggregated Data Coherence (duration)
Washing Machine	Samsung/Front Loading Clothes Washer	39-53 L (10-15 gal) (Samsung, n.d.-c)	44.7 L (11.8 gal)	16.54 ± 0.16 L/min (4.37 ± 0.04 gpm)	36.2 ± 9.0 s
Dishwasher	Samsung/Rotary Dishwasher	11.7-27.2 L (3.1-7.2 gal) (Samsung, 2015)	11.6 L (3.07 gal)	4.16 ± 0.04 L/min (1.10 ± 0.01 gpm)	64.8 ± 3.8 s
Toilet	American Standard	6.06 Lpf (1.6 gpf)	7.04 Lpf (1.86 gpf)	7.51 ± 0.10 L/min (1.98 ± 0.02 gpm)	58.8 ± 1.8 s
			5.53 Lpf (1.46 gpf)	5.98 ± 0.02 L/min (1.57 ± 0.01 gpm)	58.0 ± 6.0 s
			6.66 Lpf (1.76 gpf)	3.90 ± 0.09 L/min (1.03 ± 0.02 gpm)	113.1 ± 1.3 s
Faucet	Delta (kitchen)	6.8 L/min (1.8 gpm) (Delta, n.d.-f)	6.44 L/min (1.70 gpm)	Low Flow: 1.48 L/min (0.39 gpm) ^a	Low Flow: 12.8 s ^a
	Pfister (bathroom)	4.5 L/min (1.2 gpm) ^b (Pfister, n.d.)	6.09 L/min (1.61 gpm)		
	American Standard (bathroom)	5.7 L/min (1.5 gpm) ^b (American Standard, n.d.-f)	5.83 L/min (1.54 gpm)	Medium Flow: 2.69 to 6.74 L/min (0.71 to 1.78 gpm) ^a	Medium Flow: 21.3 to 78.3 s ^a
	Delta (bathroom)	4.5 L/min (1.2 gpm) ^b (Delta, n.d.-e)	9.39 L/min (2.48 gpm)		
	Price Pfister (utility)	Unavailable	19.0 L/min (5.02 gpm)		
	Delta (tub)	32.6 L/min (8.6 gpm) ^b	23.2 L/min (6.12 gpm)		
	Delta (tub)	32.6 L/min (8.6 gpm) ^b	16.1 L/min (4.26 gpm)		
	Delta (tub)	32.6 L/min (8.6 gpm) ^b	20.2 L/min (5.33 gpm)		
	Woodford (hose bib)	Unavailable	26.2 L/min (6.93 gpm)		
	Woodford (hose bib)	Unavailable	30.0 L/min (7.92 gpm)		
Shower	Delta	9.5 L/min (2.5 gpm)	9.01 L/min (2.38 gpm)	7.92 ± 0.11 L/min (2.09 ± 0.03 gpm) ^a	854 ± 131 s ^a
	Moen	9.5 L/min (2.5 gpm)	9.24 L/min (2.44 gpm)		
	Target	9.5 L/min (2.5 gpm)	8.48 L/min (2.24 gpm)		

Table SI2: Efficiency ratings are available for several popular automatic appliances/fixtures in the United States.

End-Use	Energy Star or WaterSense Criteria (United States Environment Protection Agency (US EPA), 2008)	Most Popular Make/Model	Rating	Reference for Rating
Washing Machine – Front Loading	802.09 L/m ³ /cycle (6 gal/ft ³ /cycle)	LG WM9000HVA LG WM5000HWA LG Signature WM49500HKA LG WM500SHKA LG WM4370HWA LG WM3670HWA Maytag MHW8200FW LG WM3770HWA Samsung WF50K7500AW Samsung FlexWash WV60M9900AV Samsung WF45K6500AW Maytag MHW3505FW LG WM8100HWA Kenmore Elite 41982 Kenmore Elite 41072	428 L/m ³ /cycle (3.2 gal/ft ³ /cycle) ^a 374 L/m ³ /cycle (2.8 gal/ft ³ /cycle) ^a Unavailable online Unavailable online 428 L/m ³ /cycle (3.2 gal/ft ³ /cycle) ^a 428 L/m ³ /cycle (3.2 gal/ft ³ /cycle) ^a 428 L/m ³ /cycle (3.2 gal/ft ³ /cycle) ^a 428 L/m ³ /cycle (3.2 gal/ft ³ /cycle) ^a 388 L/m ³ /cycle (2.9 gal/ft ³ /cycle) ^a 388 L/m ³ /cycle (2.9 gal/ft ³ /cycle) ^a 401 L/m ³ /cycle (3.0 gal/ft ³ /cycle) ^a 428 L/m ³ /cycle (3.2 gal/ft ³ /cycle) ^a 428 L/m ³ /cycle (3.2 gal/ft ³ /cycle) ^a 428 L/m ³ /cycle (3.2 gal/ft ³ /cycle) ^a 401 L/m ³ /cycle (3.0 gal/ft ³ /cycle) ^a	(LG, n.d.-b) (Energy Star, n.d.) (Energy Star, n.d.) (Energy Star, n.d.) (Energy Star, n.d.) (Energy Star, n.d.) (Energy Star, n.d.) (Samsung, n.d.-b) (Energy Star, n.d.) (Samsung, n.d.-a) (Energy Star, n.d.) (Energy Star, n.d.) (Energy Star, n.d.) (Kenmore, n.d.-l) (Kenmore, n.d.-k)

Table SI2 Cont.

End-Use	Energy Star/WaterSense Criteria	Most Popular Make/Model	Rating	Reference for Rating
Washing Machine – Top Loading	802.09 L/m ³ /cycle (6 gal/ft ³ /cycle)	LG WT5680HVA LG WT7600HWA LG WT7500CW LG WT7700HVA LG WT7200CW LG WT1901CW LG WT1150CW Kenmore Elite 31552 LG WT1501CW Kenmore Elite 31433 Whirlpool WTW8700EC Kenmore 28132 Kenmore 26132 Kenmore 27132	495 L/m ³ /cycle (3.7 gal/ft ³ /cycle) ^a 495 L/m ³ /cycle (3.7 gal/ft ³ /cycle) ^a 495 L/m ³ /cycle (3.7 gal/ft ³ /cycle) ^a 428 L/m ³ /cycle (3.2 gal/ft ³ /cycle) ^a 495 L/m ³ /cycle (3.7 gal/ft ³ /cycle) ^a 495 L/m ³ /cycle (3.7 gal/ft ³ /cycle) ^a 495 L/m ³ /cycle (3.7 gal/ft ³ /cycle) ^a 495 L/m ³ /cycle (3.7 gal/ft ³ /cycle) ^a 495 L/m ³ /cycle (3.7 gal/ft ³ /cycle) ^a 495 L/m ³ /cycle (3.7 gal/ft ³ /cycle) ^a 575 L/m ³ /cycle (4.3 gal/ft ³ /cycle) ^a 575 L/m ³ /cycle (4.3 gal/ft ³ /cycle) ^a 575 L/m ³ /cycle (4.3 gal/ft ³ /cycle) ^a 575 L/m ³ /cycle (4.3 gal/ft ³ /cycle) ^a	(Energy Star, n.d.) (Energy Star, n.d.) (Energy Star, n.d.) (Energy Star, n.d.) (Energy Star, n.d.) (LG, n.d.-a) (Energy Star, n.d.) (Kenmore, n.d.-j) (Energy Star, n.d.) (Kenmore, n.d.-i) (Energy Star, n.d.) (Kenmore, n.d.-f) (Kenmore, n.d.-d) (Kenmore, n.d.-e)
Dishwasher	15.1 L/cycle (4 gal/cycle)	Bosch Ascenta SHX3AR75UC KitchenAid KDTM354DSS Bosch 300 series SHEM463W55N Kenmore 14573 Kenmore 14543 Kenmore Elite 12793 Whirlpool WDF540PADM Kenmore 14523 KitchenAid KDTM704ESS Bosch 800 Series SHPM78WSSN Kenmore Elite 14793 KitchenAid KDTM404ESS Bosch 800 Series SHXM98W75N	11.3-21.5 L/cycle (3.0-5.7 gal/cycle) ^a 10.2-15.9 L/cycle (2.7-4.2 gal/cycle) ^a 8.8-21.0 L/cycle (2.3-5.5 gal/cycle) ^a 9.09-28.0 L/cycle (2.4-7.4 gal/cycle) ^a 9.09-28.0 L/cycle (2.4-7.4 gal/cycle) ^a 10.5-29.0 L/cycle (2.8-7.7 gal/cycle) ^a 9.09-28.0 L/cycle (2.4-7.4 gal/cycle) ^a 10.5-28.0 L/cycle (2.8-7.4 gal/cycle) ^a 10.2-15.9 L/cycle (2.7-4.2 gal/cycle) ^a 8.8-21.0 L/cycle (2.3-5.5 gal/cycle) ^a 10.4-30.3 L/cycle (2.7-8.0 gal/cycle) ^a 10.2-15.9 L/cycle (2.7-4.2 gal/cycle) ^a 8.8-21.0 L/cycle (2.3-5.5 gal/cycle) ^a	(Bosch, n.d.-d) (KitchenAid, n.d.-a) (Bosch, n.d.-a) (Kenmore, n.d.-c) (Kenmore, n.d.-b) (Kenmore, n.d.-g) (Whirlpool, n.d.) (Kenmore, n.d.-a) (KitchenAid, n.d.-c) (Bosch, n.d.-b) (Kenmore, n.d.-h) (KitchenAid, n.d.-b) (Bosch, n.d.-c)

Table SI2 Cont.

End-Use	Energy Star/WaterSense Criteria	Most Popular Make/Model	Rating	Reference for Rating
Toilet	4.85 Lpf (1.28 gpf)	St. Thomas by Icera Richmond ECO (6123.218, 6125.028) Kohler Highline Classic K-3493-0 American Standard Champion 4 Max 2586.128ST.020 Zurn Z5551-K Kohler Kelston K-3754 Toto Drake CST744S Toto Drake II CST454CEFG American Standard Acticlean 714AA151.020 Delta Turner C43908-WH Delta Prelude C43901-WH Gerber Avalanche WS-21-818 Kohler SantaRosa K-3810 American Standard Clean 2514.101 (Lowe's) Toto Eco Drake CST744E Kohler Cimarron The Complete Solution K-11451	4.85 Lpf (1.28 gpf) ^b 6.06 Lpf (1.6 gpf) 4.85 Lpf (1.28 gpf) ^b 6.06 Lpf (1.6 gpf) 6.06 Lpf (1.6 gpf) 6.06 Lpf (1.6 gpf) 4.85 Lpf (1.28 gpf) ^b 4.85 Lpf (1.28 gpf) ^b 4.85 Lpf (1.28 gpf) ^b 4.85 Lpf (1.28 gpf) ^b 4.85 Lpf (1.28 gpf) ^b 4.85 Lpf (1.28 gpf) ^b 4.85 Lpf (1.28 gpf) ^b 4.85 Lpf (1.28 gpf) ^b	(St. Thomas, n.d.) (Kohler, n.d.-c) (American Standard, n.d.-b) (Zurn, n.d.) (Kohler, n.d.-d) (TOTO, n.d.-b) (TOTO, n.d.-a) (American Standard, n.d.-g) (Delta, n.d.-g) (Delta, n.d.-c) (Gerber, n.d.) (Kohler, n.d.-f) (American Standard, n.d.-c) (TOTO, n.d.-c) (Kohler, n.d.-a)

^aLabeled Energy Star Certified

^bLabeled WaterSense Certified

Table SI3: Efficiency ratings are available for several popular faucets in the United States.

End-Use	WaterSense Criteria (United States Environment Protection Agency (US EPA), 2008)	Most Popular Make/Model	Rating	Reference for Rating
Kitchen Faucets	Purposefully not addressed	Delta Kohler Moen Brizo Vigo American Standard Kraus	5.68-15.1 L/min (1.5-4.0 gpm) 5.68-8.33 L/min (1.5-2.2 gpm) Most 5.68 L/min (1.5 gpm) Most 6.81 L/min (1.8 gpm) 6.81 L/min (1.8 gpm) 5.68-6.81 L/min (1.5-1.8 gpm) 6.81-8.33 L/min (1.8-2.2 gpm)	(Delta, n.d.-b) (Kohler, n.d.-e) (Moen, n.d.-c) (Brizo, n.d.-a) (Vigo, n.d.-b) (American Standard, n.d.-d) (Kraus, n.d.-b)
Bathroom Faucets	5.68 L/min max (1.5 gpm max)	Delta Kohler Moen Brizo Vigo American Standard Kraus	1.89-5.68 L/min (0.5-1.5 gpm) Most 4.54 L/min (1.2 gpm) 3.79-5.68 L/min (1.0-1.5 gpm) Most 5.69 L/min (1.5 gpm) 4.54-5.68 L/min (1.2-1.5 gpm) 1.89-5.68 L/min (0.5-1.5 gpm) 4.54-5.68 L/min (1.2-1.5 gpm)	(Delta, n.d.-a) (Kohler, n.d.-b) (Moen, n.d.-a) (Brizo, n.d.-b) (Vigo, n.d.-a) (American Standard, n.d.-a) (Kraus, n.d.-a)
Showers	9.46 L/min max (2.5 gpm max)	Delta Kohler Moen Grohe ALFI American Standard Hansgrohe Speakman	5.68-9.46 L/min (1.5-2.5 gpm) 5.68-9.46 L/min (1.5-2.5 gpm) 6.62-9.46 L/min (1.75-2.5 gpm) Most 9.46 L/min (2.5 gpm) Most 6.81 L/min (1.8 gpm) 5.68-9.46 L/min (1.5-2.5 gpm) 5.68-9.46 L/min (1.5-2.5 gpm) 5.68-9.46 L/min (1.5-2.5 gpm)	(Delta, n.d.-d) (Kohler, n.d.-g) (Moen, n.d.-b) (Grohe, n.d.) (ALFI, n.d.) (American Standard, n.d.-e) (Hansgrohe, n.d.) (Speakman, n.d.)

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