Improved Estimates of Peak Water Demand in Buildings: Implications for Water-Energy Savings

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α_k : Fixture mean intensity, (gpm)
$\lambda_{j,k}$: Fixture average hourly pulse arrival rate ($hour^{-1}$)
$\pi_{j,k}$: Fixture hourly multiplier
τ_k : Fixture mean duration, ($minutes$)
$\in$: Surface emittance

A: Pipe surface area, (ft^2)
C_p: Specific heat of water, ($\frac{Btu}{lb\ ^oF}$)
D_i: Inside pipe diameter, (ft)
D_o: Outside pipe diameter, (ft)
h_{air}: Overall film heat transfer coefficient, ($\frac{Btu}{hr\text{-}ft^2\text{-}^oF}$)
h_{cov}: Convection surface coefficient, $\left(\frac{Btu}{hr\text{-}ft^2\text{-}^oF}\right)$
h_{rad} : Radiation surface coefficient, $\left(\frac{Btu}{hr\text{-}ft^2\text{-}^oF}\right)$
h_w: Convective film heat transfer coefficient, ($\frac{Btu}{hr\text{-}ft^2\text{-}^oF}$)
k: Thermal conductivity of copper, ($\frac{Btu}{hr\text{-}ft\text{-}^oF}$)
k_d : Heat decay coefficient of copper L pipes, (day^{-1})
L: Pipe length, (ft)
$\dot{m}$: Mass flowrate of water, (${}^{lb_m}\!/_{hr}$)
m_l: Mass of water per lenght of pipe, (${}^{lb}\!/_{ft}$)
p_k : Fixture probability of use
q_k: Fixture flow rate, (gpm)
Q_k : Fixture 24-hour base demand flow, (gpm)
R: Time between consecutive pulses, ($seconds$)
T_a : Air temperature surrounding pipe, (^oF)
T_s : Pipe surface temperature, (^oF)
ΔT: Change in temperature, (^{o}F)
U_o: Overall heat transfer coefficient, ($\frac{Btu}{h\text{-}ft^2\text{-}^oF}$)
$V_{j,k}$: Hourly volume of water used at fixture, $(gallon)$
V^*_k : Average daily volume of water used at fixture, $(gallon)$

ABSTRACT

Current methods for estimating peak hot and cold water demands in buildings were developed 80 years ago in the seminal work of Dr. Roy Hunter at the US National Bureau of Standards. Hunter's design curve has been incorporated into the Uniform Plumbing Code (UPC) and adopted by water agencies around the world. Over the years, the performance of water fixtures and demands of water consumers have changed. Consequently, it is now widely recognized that Hunter's iconic design curve significantly over-estimates peak demand for indoor hot and cold water use. Inflated peak flow values have led to over-sized premise plumbing and improperly sized water meters, heaters, and softeners.

The hot water component of premise plumbing exemplifies the water-energy nexus on a local scale. When a building's water supply system is over-sized, it triggers a cascade of potential water-energy related problems, including:

- Inflated construction cost,
- Over-sized water meters and heaters,
- Lost revenue from inaccurate water metering,
- Wasted energy from inefficient water heating and delivery,
- Potential health issues from opportunistic bacteria (e.g., *Legionella*)

This research computes the water and energy consumption resulting from hot water use in residential plumbing systems serving households with efficient and inefficient fixtures. A novel Water Demand Calculator (WDC) is developed to estimate peak water demand expected in residential settings ranging from single-family homes to a large apartment complex. Not surprisingly, plumbing systems that serve efficient water fixtures can be smaller in scale (i.e., reduced pipe diameters, meters, heater) than the plumbing system serving standard (inefficient) water fixtures. Simulation of instantaneous water and energy consumption in a typical 2-bath residential unit shows that annual savings for both water and energy can approach 30 percent each when rightly-sized plumbing is coupled with highly efficient fixtures.

INTRODUCTION

An estimate of peak water demand is the most important factor for sizing a building's water supply system. Water demand in buildings is a random process dependent on other variables such as building size, fixture type, time of the day, occupancy rate and so on. In 1940, Dr. Roy Hunter, using the binomial distribution, developed a theoretically rigorous method to estimate the 99th percentile for peak water demand in buildings subject to congested use patterns. Hunter's design curve has been incorporated into the various plumbing codes and adopted by water agencies at home and abroad. However, with changes in fixture performance and consumer water use habits over the years, Hunter's curve significantly over-estimates peak demand for indoor hot and cold water use in contemporary applications (AWWA 2004; NIBS 2012).

Although theoretically sound, the overprediction of peak water demand by Hunter's method reflects its inability to incorporate recent water saving measures or accommodate the complexity of fixtures and other characteristics of modern plumbing (NIBS 2012). A study of residential water use trends by Coomes *et al.* (2010) suggests that low flow fixtures and appliances account for a 16 percent decline in the average daily water use over the last 20 years, thus effectively reducing water demand in buildings (Price *et al.* 2014). Consequently, following the current design practice, premise plumbing in new buildings is often designed to supply more water than necessary. To compensate for design discrepancies, ASHRAE (1987) and other professional organizations introduced modifications to Hunter's curve. Unfortunately, this makeshift approach is inconsistent and subjective. Furthermore, it does not provide a precise foundation for the design of smart high efficiency (water/energy) buildings for the future generations.

Inaccurate design guidance for water supply (i.e., premise plumbing) has profound consequences for today's new generation of water and energy conserving buildings. Obsolete water supply design guidelines produce over-sized plumbing systems and improperly sized water meters. This leads to a myriad of water – energy problems including: [i] inflated construction costs, [ii] inaccurate water monitoring and billing, [iii] wasted energy and water through inefficient water heating, and [iv] increased potential health hazards from the risk of microbial contamination (Legionella) (ANSI/ASHRAE Standard -188 2015). These issues can adversely impact owners, residents, and users of facilities throughout the public and private sectors.

According to the US Energy Information Administration (2015), energy consumption in the residential sector accounted for 22 percent of the total energy consumed in the US in 2014. In this vein, water heating is the second highest sole source of energy consumption in residential buildings next to space heating. On the average, heating water accounts for about 18 percent of total residential energy consumption in the US (US EIA 2013). Heating water is also the most energy-intensive part of the urban water-use cycle compared to the collection, treatment, and distribution of water (Vieira *et al.* 2014; Siddiqi and Fletcher 2015). There has been scant attention on the water energy-nexus at the design phase in the residential water sector.

The relationship between building water and building energy use is complex and depends on the building type, user behavior and fixture characteristics (Agudelo-Vera *et al.* 2014). Recent research on hot water distribution systems has found that many factors influence hot water energy consumption: fixture flow rates, pipe size, pipe material (Klein 2013), pipe layout (Hiller 2012; Klein 2013) and hot water waste at different fixtures (Lutz 2005; Lutz *et al.* 2014). These studies focus on one or two factors at a time. The unknown effect of combined factors on hot water energy consumption reinforces the importance of understanding the relationship between designing for hot water distribution and hot water energy consumption.

This research aims to investigate and quantify potential water and energy savings in residential buildings in which supply pipes serving efficient water fixtures are sized by an improved method. To achieve this aim, the performance of a hot water distribution system and the corresponding energy consumed a 2-bath residential building will be evaluated using combinations of the following conditions:

- **Fixture efficiency**: inefficient fixtures or efficient fixtures,
- **Pipe layout**: trunk-and-branched layout or manifold layout, and
- **Pipes sizing method**: current practice (Hunter's curve) or improved method (WDC).

METHODOLOGY

This work extends research on defining water use parameters and developing methods for estimating peak water demand necessary to right size indoor premise plumbing in buildings. The method is presented in four parts:

- **Part one** involves the estimation of fixture water use parameters from high-resolution water demand measurements at single-family homes.
- **Part two** applies the estimated fixture water use parameters to develop new methods for estimating peak water demand.
- **Part three** compares a building's premise plumbing sized by current conventional design to a similar building sized using improved estimates of peak water demand.
- **Part four** examines the impacts of the hot water pipe diameter on a building's energy consumption.

Part 1 – Parameters for estimating peak water demand

The key parameters needed to estimate peak water demand in a building are ***n*** - the number of fixtures, ***p*** - the probability that a fixture is busy, and ***q*** - the fixture flowrate. These three parameters (***n, p, q***) apply to both Hunter's (1940) binomial approach and Wistort's (1994) normal approximation of the binomial distribution to estimate the expected peak water demand.

In a review of the methods to estimate peak water demand, Omaghomi and Buchberger (2014) suggested that both Hunter and Wistort's method can be improved by using a data-centered approach to estimate parameters reflecting today's water use habits. The parameter ***n*** is a physical feature that can easily be measured, while the parameter ***q*** can be obtained from the fixture manufacturer or easily measured on site. However, the probability that a fixture is busy, ***p*** can only be estimated from an extensive water use survey. The peak hour probability that a fixture is busy (i.e., fixture ***p***-value) was calculated from a residential water use survey (IAPMO data set) with over 1000 single-family homes each having six unique fixture types. Table 1 shows the representative peak hour ***p***-values and ***q***-values for fixtures in a single-family residential home.

Table 1: Peak hour ***p***-values and ***q***-values for six fixture groups in a single-family home (Buchberger et al. 2017)

Fixture Group	**Bathtub**	**Clothes washer**	**Dishwasher**	**Faucet (Lavatory)**	**Faucet (K. Sink)**	**Shower**	**Water closet**
Probability of use	0.010	0.055	0.005	0.020	0.020	0.045	0.010
Flow rate (gpm)	5.5	3.5	1.3	1.5	2.2	2.0	3.0

Part 2 – Estimating peak water demand

In developing his curve for peak water demand, Hunter focused on large buildings with a bank of fixtures experiencing congested use (i.e., a queue of people has formed to use a fixture). Under these conditions, it was virtually certain that at least one fixture in the building would be using water at any instant during the peak period. Congested use effectively pulls the probability distribution of busy water fixtures away from the lower boundary of zero. The assumption of congested use works well with large public buildings, but complications arise in single-family homes and other small-scale dwellings with few people and few fixtures.

In smaller buildings like single-family homes, idle fixtures are the norm even during the period of peak use. The high probability of idle fixtures in the single-family home implies zero flow (stagnation) which, in turn, exerts a strong "downward pull" on the predicted peak flow. Wistort's method, a simplified version of Hunter's method is a normal approximation of the binomial distribution. Similar to Hunter's method, Wistort's method has limitations in its application to small buildings due to their high probability of idle fixtures.

A zero-truncated binomial distribution (ZTBD) was introduced to address the "downward pull" on predicted peak flow due to a high probability of idle fixtures in single-family residential homes. The ZTBD is the conditional distribution of busy fixtures in a building given that at least one fixture is busy. The ZTBD arises from the parent binomial distribution. By truncating the mass probability of zero demand and rescaling the remaining probability mass to ensure the conditional ZTBD sums to one, the predicted flows will represent the demand from at least one busy fixture.

Figure 1 illustrates two cases of binomial distribution and their corresponding ZTBD. As the number of fixture increases and the probability of zero flow approaches zero ($P_o \rightarrow 0$), there is a smooth transition from the ZTBD to the binomial distribution. Hence, the ZTBD provides the missing link needed to extend the binomial design framework across the full spectrum from large public buildings to small private dwellings.

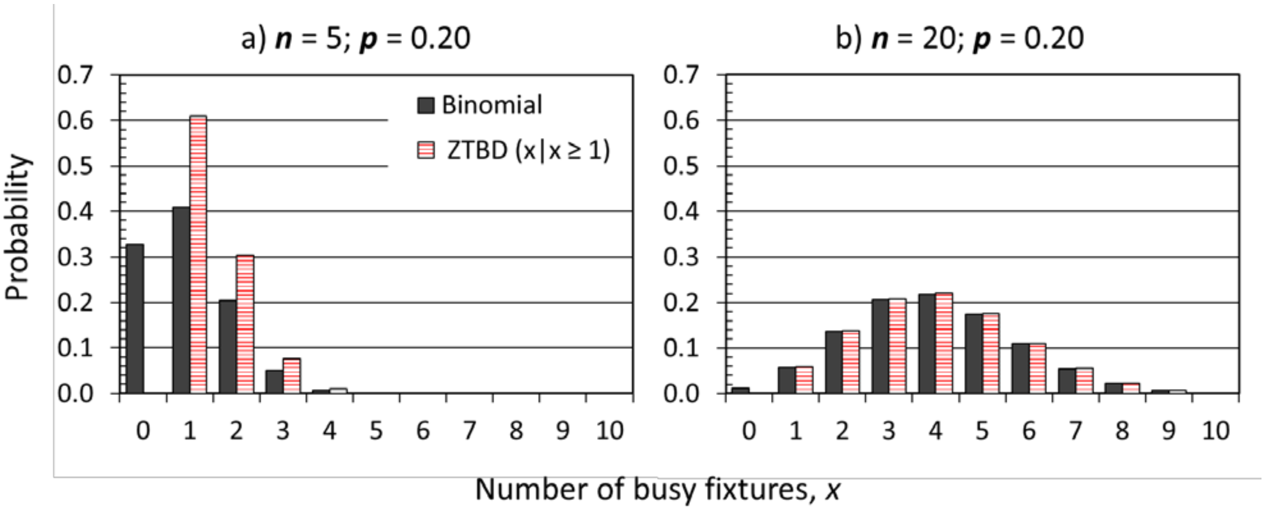

Figure 1: Binomial Distribution and Zero Truncated Binomial Distribution (ZTBD) of busy fixtures in a group of (a) ***n*** = 5 (b) ***n*** = 20 fixtures each with a probability ***p*** = 0.20 of being in use.

Findings by Buchberger *et al*. (2017) indicate that no single method is suitable to estimate peak water demand for all sizes of building. As a building size and its number of fixtures increases, the building's water demand transitions from discrete to continuous random pulses. A water demand calculator (WDC) was created in Microsoft Excel to select an appropriate method for estimating peak water demand depending on the combination of parameters ***n***, ***p***, ***q***. The WDC selects from methods such as the exhaustive enumeration of the binomial method, a modified Wistort's method using the ZTBD and Wistort's method. Results from the WDC represent the improved estimates of peak demand used in this report. Further details on the WDC can be found in Buchberger *et al*. (2017).

Part 3 – Sizing premise plumbing in a single-family home.

The hot water premise plumbing layout for a typical 2-bath home is shown in Figure 2. Results of pipe sizing for hot water use at this home are summarized in Table 2 for two instances: (1) Estimated peak demand and size pipe using Hunter's Curve (current practice) and (2) Estimated peak demand and size pipe using WDC (improved method).

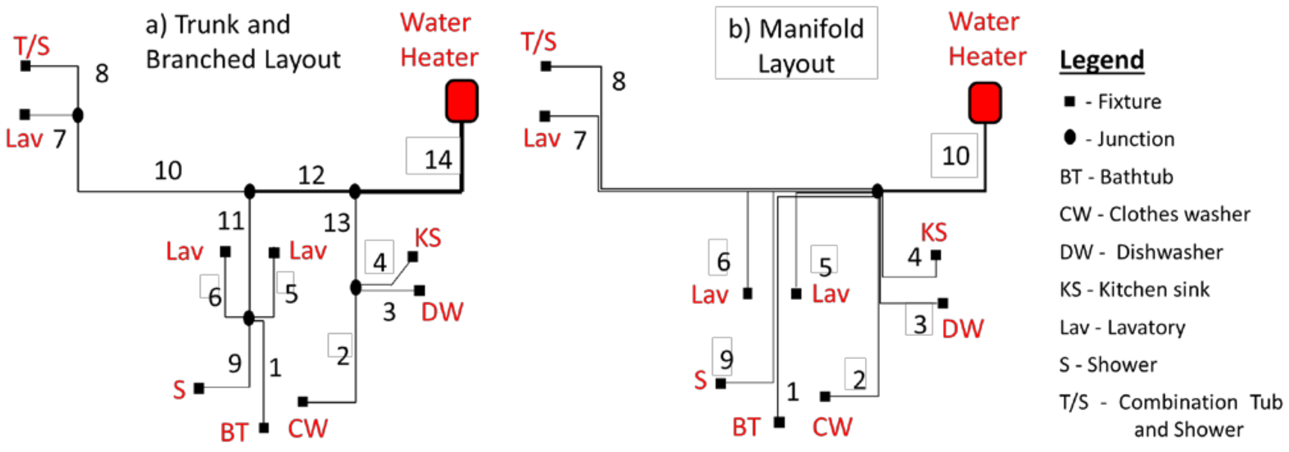

Figure 2: Hot water distribution in a single-family home for a) trunk-and-branch layout and b) manifold layout

Comparing estimates from current practices to the improved WDC method in Table 2 reveals that the design demand for single fixtures using the current method differs from the actual fixture flow rate. For instance, pipes sized by the current practices gives a 3.3 gpm for a bathtub, while the improved method gives a 5.5 gpm. This is due to the fact that Hunter's method is not suitable for premise plumbing design with single fixtures. To arrive at design demand values for single fixtures using the current method, Hunter's curve had to be extrapolated from 5 Fixture Units (FU) and 4 gpm to 1 FU and 1 gpm. Furthermore, to reconcile the inconsistency in design demand and demand flows, the UPC set a minimum allowable pipe size of 1/2 inch. This minimum allowable pipe size over compensates for dishwashers and lavatory faucets, but ironically under compensates for bathtubs and combination tub showers.

Table 2: Estimated water demand and corresponding pipe sizes (Copper L) for current practice and the proposed improved method (WDC) for trunk and branch layout shown in Figure 2

Link	Single fixtures and links with more than one fixture serviced by pipe	Current Practice			Improved Method (WDC)		Pipe length (feet)
		UPC Fixture Units (FU)	Peak Demand (gpm)	Pipe Size (in)	Peak Demand (gpm)	Pipe Size (in)	
1	BT	4	3.3	1/2	5.5	**3/4**	5.3
2	CW	4	3.3	1/2	3.5	1/2	10.1
3	DW	1.5	1.4	**1/2**	1.3	3/8	12.8
4	KS	1.5	1.4	1/2	2.2	1/2	9.7
5	Lav	1	1.0	**1/2**	1.5	3/8	8.4
6	Lav	1	1.0	**1/2**	1.5	3/8	9.5
7	Lav	1	1.0	**1/2**	1.5	3/8	2.1
8	T/S	4	3.3	1/2	5.5	**3/4**	7.2
9	S	2	1.8	**1/2**	2.0	3/8	5.8
10	**Links 7, 8**	5	4.0	1/2	5.5	**3/4**	13.0
11	**Links 1, 5, 6, 9**	8	6.5	3/4	7.0	3/4	10.5
12	**Links 10, 11**	13	10.0	**1**	7.5	3/4	11.8
13	**Links 2, 3, 4**	7	6.3	3/4	4.8	3/4	8.6
14	**All fixtures**	20	14.0	**1-1/4**	9	1	27.4

- Grey cells indicate links where the pipe diameters for current practice differ from diameters for the improved method.
- Bold red font indicates the case with the larger pipe diameter.
- Pipe sizes are for hot water pipes, based on peak demand and maximum water velocity of 5 ft/sec

Part 4 – Simulating hot water demand pulses and estimating energy consumed.

Background

The daily energy needed to heat the hot water tank depends on the total daily volume of water used rather than the peak water demand. Because the WDC tool (mentioned in Part 2) gives peak flow rates but not daily water volumes, a different approach was needed to simulate the volume of hot water drawn during household fixture use. The Poisson Rectangular Pulse (PRP) concept developed by Buchberger and Wu (1995) was used to generate indoor residential hot water pulses on a 1-second time scale. The generated demands were input to the public domain computer code EPANET to simulate instantaneous hot water use at fixtures inside a typical household for a period of one year. Figure 3 shows the flowchart linking PRP water demands with EPANET.

Simulating PRP Demand Pulses

With the PRP approach, residential users are assumed to arrive during hour *j* at household fixture group *k* according to a Poisson process with a constant rate $\lambda_{j,k}$ given by,

$$\lambda_{j,k} = \pi_{j,k} \left(\frac{Q_k}{\alpha_k \, \tau_k} \right) \qquad [1]$$

In this expression, $\pi_{j,k}$ is the dimensionless hourly multiplier reflecting the diurnal demand pattern of indoor water use at fixture group *k* (see Figure 4). Q_k is the average continuous 24-hr base demand for a *single* fixture in group *k* (see Table 4). The denominator in Equation [1] is the product of the mean intensity α_k and mean duration τ_k of the water pulse for fixture group *k* (see Table 5). The four terms on the right-hand-side of Equation [1] were estimated from residential water use information in the IAPMO database.

The 24-hr base demand for a *single* fixture in fixture group *k* having n_k identical fixtures is given by,

$$Q_k = \frac{V_k^* / n_k}{1440 \, {}^{minutes}\!/_{day}} \qquad [2]$$

Where V_k^* is the average volume of water used per day at a fixture group of n_k identical fixtures. If V_k^* is expressed as gallons per day, then the resulting value for Q_k given in Equation [2] is gpm per fixture.

The dimensionless multiplier during hour *j* for fixture group *k* is the ratio of the hourly consumption at the fixture group $V_{j,k}$ to the average volume of water used per hour at the fixture group and is given by.

$$\pi_{j,k} = \frac{V_{j,k}}{V_k^* / 24} \qquad [3]$$

At each fixture group *k*, the daily average of the hourly multipliers is unity, $\frac{1}{24} \sum_{j=1}^{24} \pi_{j,k} = 1.0$

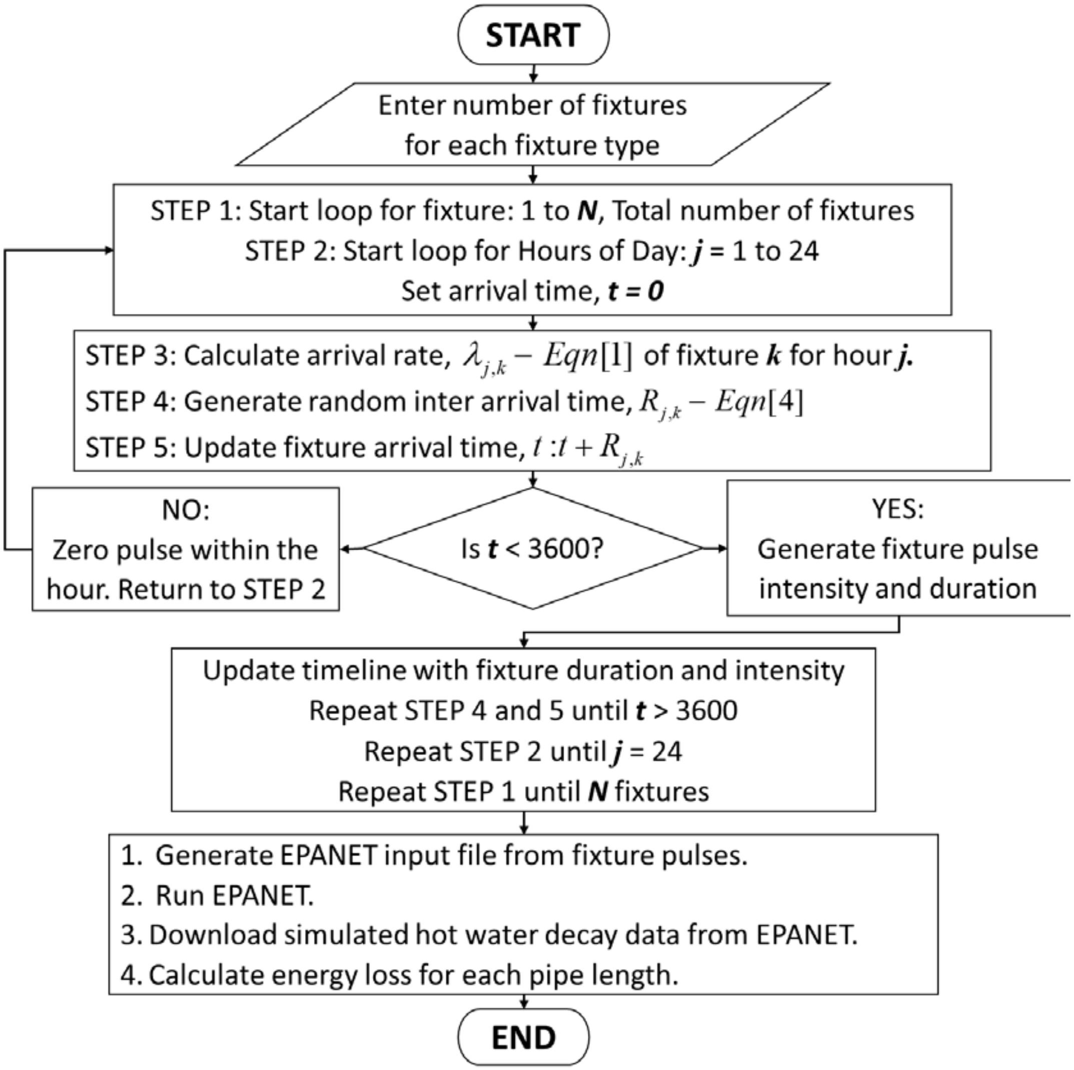

Figure 3: Flowchart to generate PRP pulses necessary and perform hydraulic simulations in EPANET

Since the arrival rate at a fixture follows the Poisson process, the time between water pulses is exponentially distributed. The time $R_{j,k}$ between consecutive pulses during hour ***j*** at fixture group ***k*** is

$$R_{j,k} = -\frac{Ln(U)}{\lambda_{j,k}} \qquad [4]$$

where *U* is a uniform random variable between [0, 1]. For generated pulse arrivals, random pulse intensities and duration are simulated with a log-normal distribution. The necessary parameters to simulate fixture pulse characteristics using the PRP method were derived from the IAPMO data set for six unique fixtures groups identified in the IAPMO database. Each fixture was categorized as either efficient or inefficient based on the water consumption per use. Table 3 shows the fixture classification criteria. Note that Bathtubs and Faucets (Kitchen sink and Lavatory) were not categorized by efficiency.

Table 3: Criteria for fixture efficiency

Fixture	Efficiency Criteria	Efficient Fixtures	Inefficient Fixtures
Clothes water	Gallon per load	≤ 30	> 30
Dishwasher	Gallon per use	≤ 3	> 3
Shower	Gallon per minute	≤ 2.5	> 2.5

The fixture PRP parameters namely daily base flow, mean and standard deviation of pulse intensity and duration are in Tables 4 and 5, respectively. Results from the water use survey showed a slight difference in weekend water use consumption and patterns when compared to weekday water use. Hence, the simulations of demand pulses included the weekday-weekend effect using the fixture base flows in Table 4 and multipliers shown in Figure 4 to generate the arrival rate at a fixture. There was no difference in the pattern of water use between efficient and inefficient fixtures.

Table 4: 24-hour base demand for individual fixtures in six fixture groups in single-family home

Fixture	Inefficient Fixtures (gpm)		Efficient Fixtures (gpm)	
	Weekday Base Flow	Weekend Base Flow	Weekday Base Flow	Weekend Base Flow
Bathtub	0.0035	0.0040	0.0035	0.0040
Clothes washer	0.0243	0.0364	0.0130	0.0198
Dishwasher	0.0018	0.0020	0.0017	0.0020
Faucet*	0.0055	0.0060	0.0055	0.0060
Shower	0.0149	0.0162	0.0120	0.0131
Water Closet	0.0158	0.0172	0.0080	0.0092

* Faucet represents both kitchen sink and lavatory

Table 5: PRP fixture parameters - Pulse characteristics

Fixture	Pulse characteristics	Inefficient Fixtures		Efficient Fixtures	
		α, Intensity (gpm)	τ, Duration (minutes)	α, Intensity (gpm)	τ, Duration (minutes)
Bathtub	*Average*	4.47	4.99	4.47	4.99
	Standard dev.	1.22	2.73	1.22	2.73
Clothes washer	*Average*	3.79	12.96	2.36	10.54
	Standard dev.	0.95	2.98	0.90	2.33
Dishwasher	*Average*	1.16	4.06	1.02	2.05
	Standard dev.	0.27	2.22	0.26	0.59
Faucet*	*Average*	0.97	0.61	0.97	0.61
	Standard dev.	0.23	0.22	0.23	0.22
Shower	*Average*	3.14	7.26	1.87	8.55
	Standard dev.	0.56	2.64	0.33	2.85
Water Closet	*Average*	2.78	1.29	2.14	0.91
	Standard dev.	0.75	0.54	0.57	0.34

* Faucet represents both kitchen sink and lavatory

Note that different methods were employed to arrive at the parameters for the WDC and the PRP method. The fixture peak hour ***p***-values shown in Table 1 were estimated from fixture duration of use, while the fixture base flow (see Table 4) and hourly multipliers (see Figure 4) were estimated from the volume of water use at the fixture.

Since the IAPMO database did not distinguish between water use at the lavatory and kitchen sink, the PRP parameters for faucet were applied to generate arrival times for both the lavatory and the kitchen sink. About 20 percent of the measured faucet flow rates in the database was greater than 2 gpm. Therefore, the arrivals at faucet were split 80-20 for pulses at a lavatory and kitchen sink respectively. For example, only 80 percent of the arrivals at a lavatory was actual water use pulses at the lavatory. Similarly, only 20 percent of arrivals at a kitchen sink were actual pulses at the kitchen sink. The kitchen sink pulse characteristics were 1.52 (± 0.50) gpm and 1.01 (± 0.52) minute for the intensity and duration of flow respectively.

The simulated frequency and volume of hot water demand pulses at fixtures were remarkably similar to the expected values based on the input parameters supplied in Tables 4, 5 and Figure 4. Table 6 shows good agreement between the expected and simulated daily fixture frequency of use and volume. The difference between the expected and simulated daily number of events and volume was less than ± 2 percent. Also, the small standard error indicates the accuracy of the mean simulated pulse arrivals and pulse characteristics.

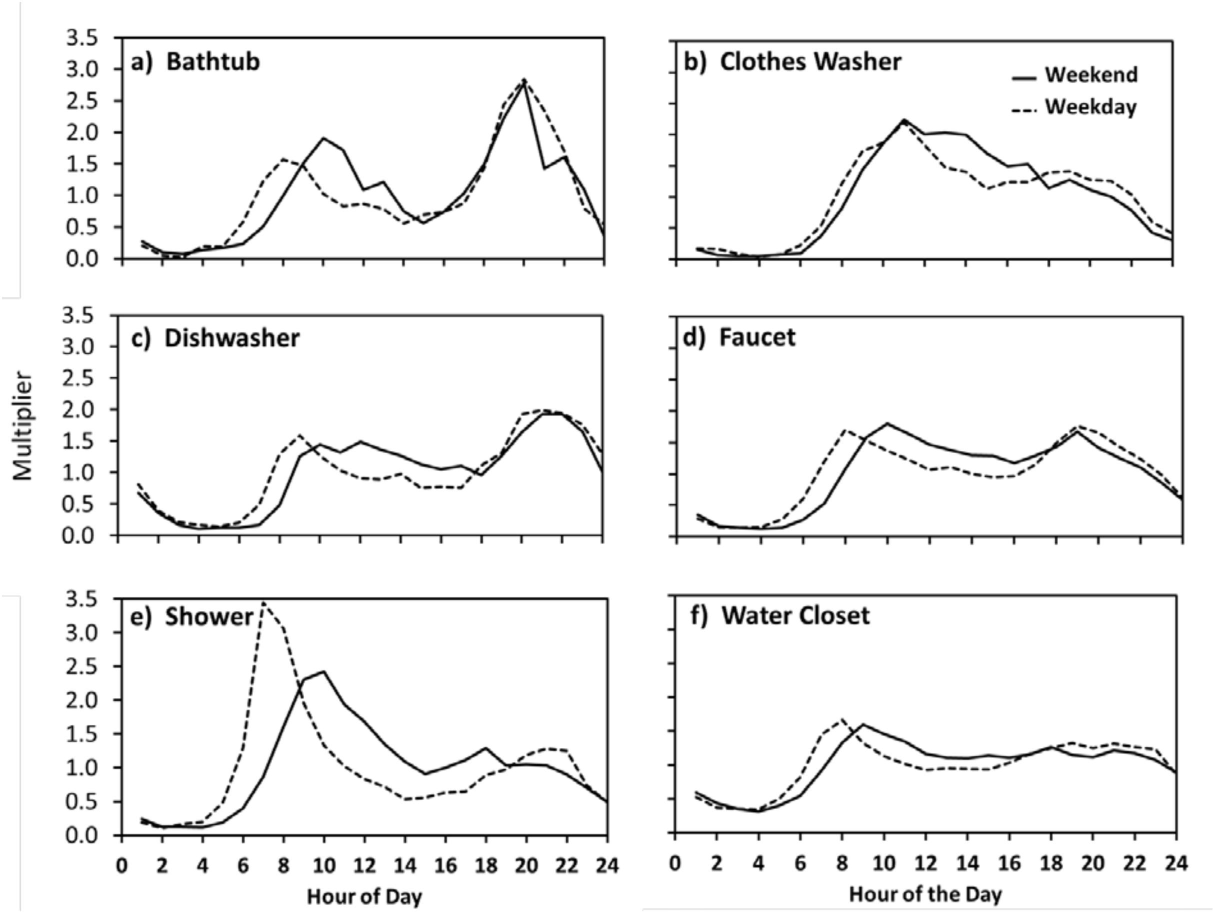

Figure 4: Fixture demand multipliers for weekday and weekend water use

Table 6: Expected and simulated pulse characteristics for hot water fixtures

Fixtures	[A] Expected		[B] Simulated		Percentage difference between [A] and [B]		Standard error in simulation	
	Events /Day	Hot Water Volume/Day (gallons)	Events /Day	Hot Water Volume/Day (gallons)	Events /Day	Volume /Day	Events / Day	Volume /Day (gallons)
Bathtub	0.23	4.52	0.23	4.61	-1.3	1.9	0.02	0.47
Clothes washer	0.95	16.14	0.94	15.82	-1.1	-2.0	0.05	1.04
Dishwasher	1.26	2.64	1.27	2.65	0.7	0.5	0.06	0.13
Kitchen Sink	2.75	3.30	2.77	3.36	0.9	1.9	0.09	0.13
Lavatory	10.98	5.13	10.94	5.12	-0.4	-0.3	0.17	0.09
Shower	1.11	15.43	1.11	15.38	0.1	-0.3	0.06	0.83

EPANET Setup

EPANET has a minimum 1-minute timescale for its hydraulic simulations. Therefore, the fixture pulses generated on a 1-second scale were consolidated into a 1-minute time scale before performing hydraulic simulations in EPANET. The duration of the pulse flow was rounded to the nearest minute (i.e., 85 seconds is rounded down to 1 minute, while 95 seconds rounded up to 2 minutes). To preserve the simulated pulse volume, the pulse intensity was adjusted to fit the new pulse duration (See Figure 5).

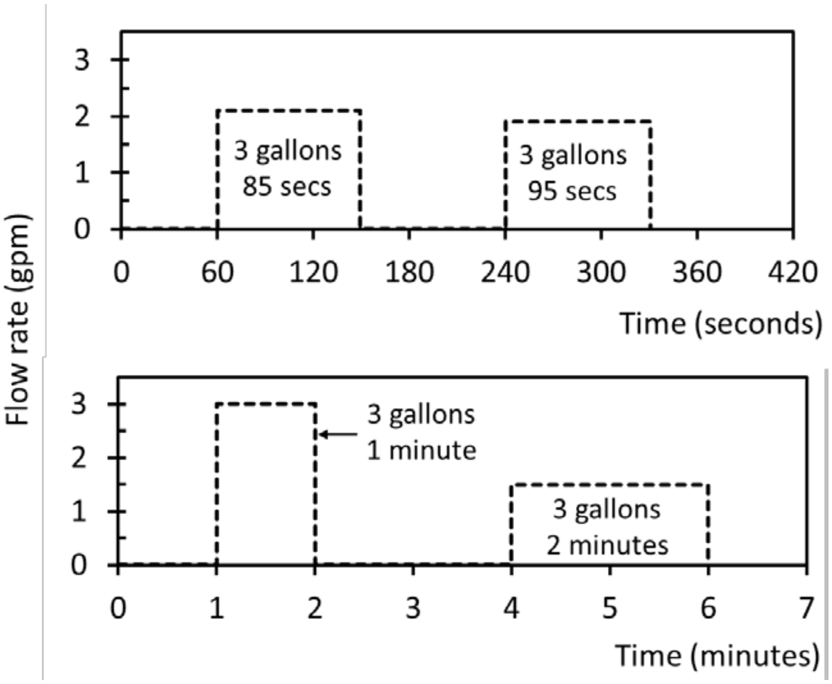

Figure 5: Illustration of adjusted pulse duration with preserved mass

The EPANET first-order decay function for chlorine concentration was applied to simulate hot water cooling in pipes. Depending on the pipe size and material, the rate at which heat dissipates through the pipe wall differs. The decay coefficient, k_d of heat through copper L pipes as shown in Table 7, was calculated using Equation [5] for the different pipe sizes. Note that Equation 5 is a derived expression from combining the heat capacity formula $Q = mc\Delta T$ and heat transfer formula $Q = \frac{kA\Delta T}{d}$. A step by step procedure can be found in Omaghomi (2018) - in review. These derived decay coefficients for copper L pipes are the bulk coefficient for each link in the EPANET network setup.

$$k_d = \frac{AU_o}{m_l C_p} \qquad [5]$$

$$\text{Where } U_o = 1 \Big/ \left(\frac{D_o}{D_i h_w} + \frac{D_o ln(D_o/D_i)}{2k} + \frac{1}{h_{air}} \right)$$

$$h_{air} = h_{\text{cov}} + h_{rad}$$

$$h_{\text{cov}} = 0.27 \left[\frac{|T_s - T_a|}{D_o} \right]^{0.25}$$

$$h_{rad} = \frac{\in \text{x}\, 0.1714 \,\text{x}\, 10^{-8} \left[(T_a + 459.6)^4 - (T_s + 459.6)^4 \right]}{(T_a - T_s)}$$

$$\text{Dull} \in = 0.44, \qquad \text{Bright} \in = 0.08$$

$$\text{Stefan-Boltzman Constant} = 0.1714\text{x}10^{-8} \left(\frac{Btu}{hr - ft^2 - R^4} \right)$$

Table 7: Heat decay coefficient for different sizes of uninsulated Copper L pipes from equation [5]

Nominal pipe size (inches)	1/4	3/8	1/2	3/4	1	1-1/4	1-1/2	2
k_d, Heat decay coefficient, (day^{-1})	129	87.5	65.5	41.7	30.1	23.4	19.0	13.7

Other assumptions considered for running EPANET are the desired temperature depending on the type of fixture and the ambient water temperatures as detailed in Tables 8 and 9.

Table 8: Typical hot water temperatures at fixtures and implied hot/cold water mix

Fixture	**Usage Temperature (°F)**	**% Hot**	**% Cold**
Bath Filling	95	63	37
Clothes washer (hot)	118	100	0
Clothes washer (warm)	87	51	49
Dishwasher	118	100	0
Faucet	105	79	21
Shower and Tubs	110	87	13

NOTE:

Hot Water Temperature (°F*)*	*118*
Cold Water Temperature (°F*)*	*55*

- *Fixture usage temperatures are based on recommendations from ASHRAE Applications Handbook.*
- *Cold water temperature represents an annual average temperature for Cincinnati Ohio adopted from US Climate Data.*
- *Cold water temperature was used ONLY to estimate the mixing ratio of hot to cold water for a usage temperature.*
- *Clothes washer warm wash temperature is assumed to be a simple average of cold and hot water temperatures.*
- *Water heater set temperature is assumed to be 120 (°F).*
- *Clothes washer (hot) and dishwasher are set at maximum temperature.*

Table 9: Cincinnati mean monthly temperatures (U. S. Climate Data 2017)

Month	Temperature (°F)	Month	Temperature (°F)
January	30.5	July	76.5
February	35.5	August	74.5
March	44.5	September	68.0
April	54.0	October	55.5
May	64.0	November	45.5
June	72.5	December	35.4

Energy Calculations

For this research, the energy calculations on heated water are focused on hot water distribution system (HWDS) excluding the water heater. Figure 6 shows two different outcomes of energy in hot water after it has left the heater: it is dissipated (between uses) along the pipe, or it is delivered (during use) to the end use fixture. The water heater is assumed to be 100 percent efficient, always delivering hot water at a set temperature of 120 °F. The pipes in HWDS are a control volume in which previously heated water cools to room temperature. It is assumed that there is no water loss from leaking pipes and no extra energy is required to move the water through the HWDS. Other assumptions relevant to the calculations are, water temperature is constant across the pipe length, the effect of longitudinal mass dispersion (or energy) is ignored as EPANET assumes plug flow, and finally, the pipes are not insulated. The ambient temperatures were also assumed to be constant throughout the month. The water temperature at the fixture during use represents actual usage temperature, needed to calculate the energy delivered. The water temperature in the pipes was used to calculate the energy dissipated between uses.

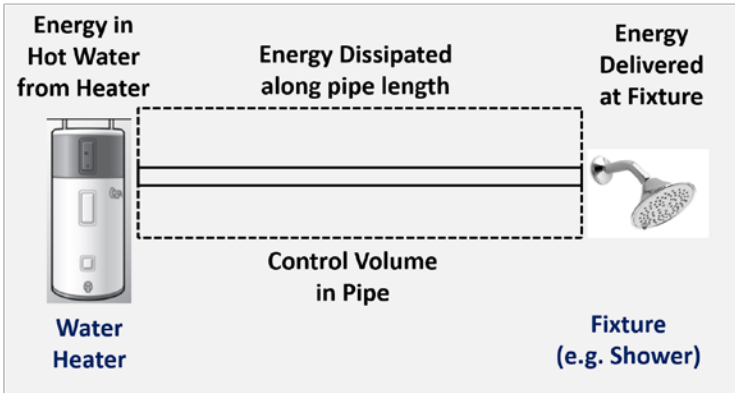

Figure 6: Energy balance in a building's pipe network

The energy consumed related to hot water demand was analyzed for the HWDS in a 2-bath residential building for the following four scenarios:

(i) inefficient fixtures versus efficient fixtures,
(ii) trunk-and-branch versus manifold layout with efficient fixtures,
(iii) pipe sizes determined by the current practices (Hunter's curve) versus improved estimates (WDC) and,
(iv) hot water use per unit in a multi-unit building versus single unit building.

Since energy is conserved, the energy required to raise the temperature of one gallon of water through 1 ^{o}F is the energy dissipated when the temperature of one gallon of water cools by 1 ^{o}F. Therefore, the total energy delivered and dissipated from a hot water draw is calculated using Equation [6].

$$E_{Total} = \underbrace{\int_t c_p\, \dot{m}\, \Delta T_t \; dt}_{E_1} + \underbrace{\int_t A\, U_o\, \Delta T_t \, dt}_{E_2} \qquad [6]$$

Note that the calculation differentiates between flowing and zero-flow states. In a zero-flowing state, $\dot{m} = 0$ so the flow-dependent term (first part of Equation [6]) disappears. The second part of Equation 6 (E_2) is the heat loss through the pipes in the flowing and zero-flow states. E_2 is calculated by integrating the heat transfer rate through the pipe over time, ***t***.

In a trunk-and-branch network, there are situations where the cooling of hot water in a pipe with multiple fixtures downstream is interrupted by another hot water pulse from a different fixture. The energy loss in the shared pipe is assigned to the fixture with the most recent pulse until another fixture becomes active. For instance, Link 10 in Table 2 is shared by the lavatory and tub/shower-nodes 7 and 8 respectively. Figure 7 shows overlap in heat loss from the 2nd and 6th pulse. The energy dissipated after the 2nd and 6th pulses will be attributed to node 7 even if the heat from the 1st and 5th pulse at node 8 primed the system.

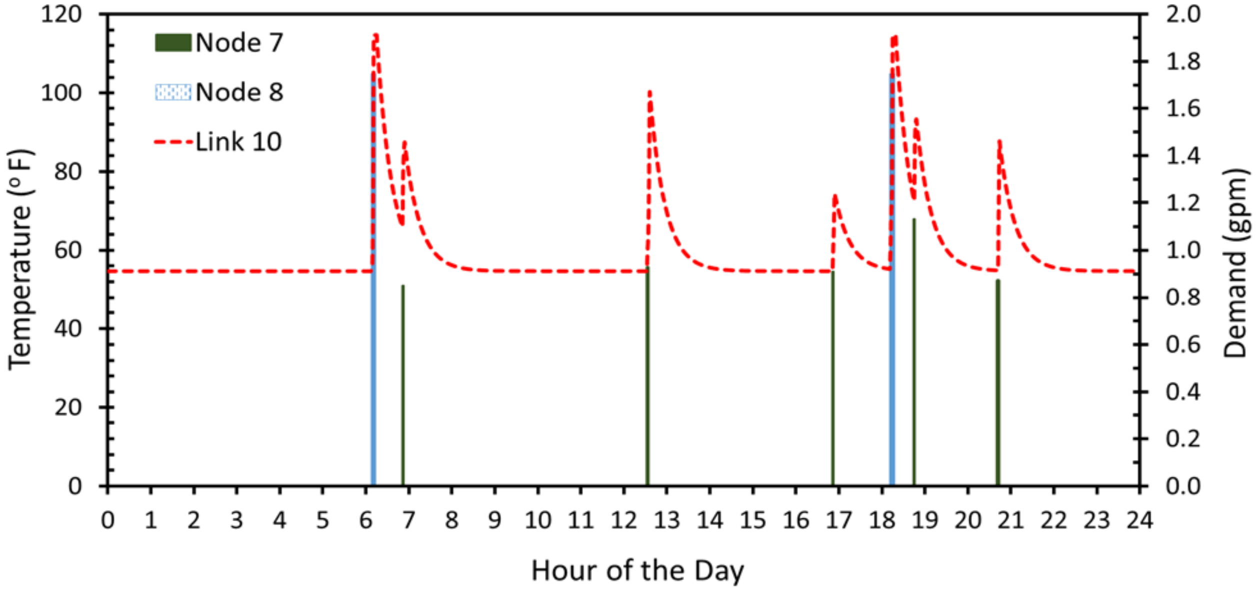

Figure 7: 24-hour timeline of hot water demand pulses and temperature decay resulting from the use of two fixtures in a 2-bath unit in Figure 2a

RESULTS AND DISCUSSION

EPANET was used to simulate the flow and change in temperature of hot water through a typical 2-bath premise plumbing system. The water use demands at individual fixtures were generated using the PRP process. Temperature readings were taken at the fixtures and their connecting pipes. Results for simulated hot water demand pulse and the energy consumed are summarized in Tables 10, 11 and 12 for various scenarios concerning fixture efficiency, network configuration and network sized by current practice and improved estimates. The total energy entering the pipes as hot water was categorized into two parts: Energy utilized at the fixtures due to hot water delivered (E_1), and energy dissipated due to heat loss through the pipe walls (E_2).

Inefficient and Efficient Fixtures

Due to only fixture efficiency, Figure 8 and Table 10 shows a 30.6 percent reduction in the volume of hot water consumed and a corresponding 30.6 percent reduction in total energy consumed. The amount of annual savings in energy is directly related to the reduction of hot water delivered.

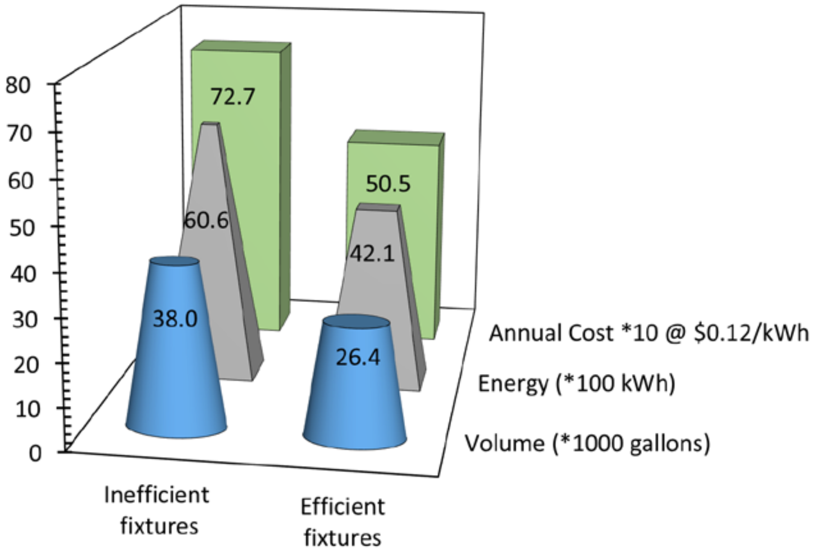

Figure 8: Annual hot water volume, energy consumed and energy cost in a 2-bath home with inefficient and efficient water fixtures

Premise Plumbing Configuration

The effect of pipe size is important when comparing the annual energy consumed in a 2-bath building with a trunk-and-branch network to a similar building with a manifold network with efficient fixtures. In the manifold network, each fixture had a dedicated pipe that runs the full length as the corresponding fixture in the trunk-and-branch layout (see Figures 2a and 2b).

The total length of pipes in the manifold layout was 263.2 feet holding 4.1 gallons of water, while the trunk-and-branch layout was 142.5 feet with 3.1 gallons of water. However, for the hot water line to any given fixture, the volume of the manifold layout never exceeded the volume of water in the trunk-and-branch layout. This means that, during a hot water use event, less water required flushing, thus hot water was delivered at higher temperatures to the fixtures in the manifold system. Furthermore, owing to its smaller pipe volume, the heat lost during waiting periods between hot water demand was less for the manifold system than the trunk and branch system. Table 11 shows the average annual energy delivered (E_1) in the manifold network was 11.3 percent greater than the trunk-and-branch layout, meanwhile the average annual energy loss in the pipe (E_2) reduced by 5.9 percent.

Table 10: Annual hot water/energy consumed in a 2-bath residence with trunk-and-branch network sized by Hunter's curve and new WDC

Scenario	Statistics	Volume (gallons)	E_1 (kWh)	E_2 (kWh)	Total Energy Consumed (kWh)	Percentage Difference in Average Volume	Percentage Difference in Average Total Energy Consumed
Hunters Curve and Inefficient Fixture	Average	38050	4260	1380	6060	Reference Case	
	Standard dev.	849	112	7	132		
Hunters Curve and Efficient Fixture	Average	26400	2640	1360	4210	- 30.6	- 30.6
	Standard dev.	483	66	8	75		
New WDC and Efficient Fixture	Average	26400	2670	1230	4210	- 30.6	- 30.6
	Standard dev.	483	65	7	75		

Table 11: Annual hot water/energy consumed in a 2-bath residence with trunk-and-branch and manifold pipe network sized with a new WDC method

New WDC and Efficient Fixture	Statistics	Volume (gallons)	E_1 (kWh)	E_2 (kWh)	Total Energy Consumed (kWh)	Percentage Difference in Energy Delivered	Percentage Difference in Energy Dissipated
Trunk-and-Branch Layout	Average	26400	2670	1230	4210	Reference Case	
	Standard dev.	483	65	7	75		
Manifold Layout	Average	26400	2970	1160	4210	11.3	- 5.9
	Standard dev.	483	70	7	75		

Table 12: Annual hot water/energy per unit consumed in a building with 2-bath units sized with the new WDC method

New WDC and Efficient Fixture	Statistics	Volume (gallons)	E_1 (kWh)	E_2 (kWh)	Total Energy Consumed (kWh)	Percentage Difference in Average Volume	Percentage Difference in Average Total Energy Consumed
1 Unit/ Building	Average	26400	2670	1230	4210	Reference Case	
	Standard dev.	483	65	7	75		
2 Units/ Building	Average	26450	2740	1320	4220	0.18	0.23
	Standard dev.	370	52	8	59		
4 Units/ Building	Average	26480	2710	1360	4220	0.28	0.33
	Standard dev.	299	41	5	48		

NOTE: The terms E_1 and E_2 are as described in Equation 6

Pipe Sizing Method

Updating the peak demand estimates and right-sizing the premise plumbing accordingly (improved method) for a 2-bath home resulted in an 18 percent decrease in the total volume of hot water within the distribution network. There was a mix of increase and decrease in single fixture pipe size. For the 2-bath home example, the decrease in volume is largely from pipes serving two or more fixtures downstream. Reduced pipe sizes result in a corresponding decrease in the waiting time or hot water at a fixture, given the same flow rate.

As shown in Table 7, the heat decay coefficient of a small pipe is greater than those of larger pipe (e.g., 65.5 per day for 1/2" pipe and 41.7 per day for a 3/4" pipe). Given the same demand pulse characteristics and pipe length between the heater and a fixture, the temperature at a fixture will differ solely due to the pipe size difference. The temperature of hot water delivered at a fixture with a smaller pipe will be slightly lower than that of a similar fixture at the end of a larger pipe. The higher heat decay coefficient in smaller pipes are responsible for the higher rate of heat loss from the pipes.

Due to the difference in pipe sizes from the pipe sizing methods, about 1 percent increase in the annual energy delivered and 9.7 percent decrease in the annual energy dissipated can be calculated from the values in Table 10. Depending on the fixture efficiency, pipe sizing method and pipe layout, the average annual energy consumed related to pipe characteristics (E_2) accounted for about 23 percent to 32 percent of the total annual energy consumed. Correspondingly, the bulk of the annual energy consumed related to water heating, i.e. energy delivered (E_1), accounted for about 62 percent to 70 percent of the total annual energy consumed.

Building Size

The energy simulations were extended to buildings with multiple of 2-bath units to investigate hot water and energy consumption in larger buildings. The national average annual energy consumed due to water heating was 4,471 kWh and 5,403 kWh per single-family household attached and detached respectively (US EIA 2013). In the same report, the average annual energy consumed by water heating decreased per household for multi-apartment buildings. The results in Table 12 show no notable change in the average annual energy consumed per unit in buildings with 2 or 4-units. This is because the demand pulses for the multi-unit building were simply multiple simulations of hot water use in a single unit.

Although this research did not report any effect of reduced pipe size on energy consumption in multi-apartment buildings, Table 13 shows there will be significant reductions in the expected demand and the corresponding pipe size for pipe mains supplying water to multiple units. There is greater than 47 percent reduction in estimated demand leading to a drop in two or more pipe sizes in larger buildings with multiple units.

Table 13: Pipe sizes for water demand in large buildings

Building Size: Number of Units	Number of Fixtures	Hunters Curve		New WDC		Percentage Decrease in Expected Flow	Number of Pipe Size Drop
		Demand (gpm)	Pipe Size (inches)	Demand (gpm)	Pipe Size (inches)		
1	11	17	1-1/4	9	1	-47.1	1
2	22	29	2	11	1	-62.1	3
4	44	44	2	15	1-1/4	-65.9	2
10	110	75	3	22	1-1/2	-70.7	3
20	220	125	3-1/2	35	2	-72.0	3
50	550	240	5	71	2-1/2	-70.4	4
100	1100	375	6	125	3-1/2	-66.7	3

These results are subject to the following limitations:

- Fixture parameters extracted from the IAPMO database were calculated per unit fixture. No adjustments were made based on the number of residents in the surveyed households. Therefore, the simulated demand pulses are representative of an average of 2.72 residents per household.
- A Lutz (2005) discussed, 20 percent of hot water wasted. The IAPMO water use database had results for all water use events (cold and hot). Therefore, the fixture pulse parameters from the IAPMO database already incorporates the peculiar human behavior of waiting for hot water. The energy delivered (E_1) in this report accounts for both wasted and useful hot water.

CONCLUSION

Hot water distribution is a key component of premise plumbing. It is therefore important to understand how changes in fixture efficiency and pipe sizing affect hot water and energy consumption in residential buildings. In this study, the generation of realistic hot water pulses at individual fixtures using MATLAB and simulation of temperature changes within pipes using EPANET provided clear insights on the water/energy implications of right-sized premise plumbing systems.

Sizing pipes with the new WDC method reduce the amount of water between the heater and a fixture, thus minimizing structural waste by reducing the waiting time for hot water at a fixture. Similarly, the use of efficient fixtures in rightly-sized premise plumbing systems reduces water and energy consumption associated with hot water use in the building. The 2-bath example in this report shows a 30 percent reduction in annual energy consumed resulting in about \$222 of annual cost saving for a single-family residence at a Cincinnati rate of \$0.12/kWh.

Review of simulated short duration, low flow pulses especially at the lavatory and kitchen sink reveals that only about half of the hot water drawn from the heater is delivered to the fixture. This result is consistent with field observation of Lutz *et al.* (2014).

If the time between consecutive hot water use exceeds two hours, the hot water line will cool to room temperature. In this case, energy added by the water heater does not reach the end use, but instead dissipates along the supply line. Insulating pipes will reduce the rate of heat loss in the pipe. Investigating the effect of insulated pipes on the total energy consumed is suggested to quantify the cost-effectiveness of hot water pipe insulation. EPANET does not simulate longitudinal mass or heat dispersion in pipes. Future work should consider comparing measured hot water pulses to EPANET simulated water demands to assess the importance of including dispersion when simulating the temperature of the water reaching a fixture.

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