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Peak Water Demand Study

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Peak Water Demand Study

Probability Estimates for Efficient Fixtures in Single and Multi-family Residential Buildings

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- C.J. Lagan, Senior Manager, Testing & Compliance, LIXIL Water Technology, American Standard, U.S.
- E.J.M. (Mirjam) Blokker, PhD MSc, Principal Scientist – Water Infrastructure, KWR Watercycle Research Institute, the Netherlands.
- Eric Yeggy, Director of Technical Affairs, Water Quality Association, U.S.
- Jim Lutz, Researcher, Hot Water Research, U.S.
- Gary Klein, Principal, Gary Klein Associates, U.S.

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List of Symbols

$A_{0.99}$	Modified frequency factor
BT	Bathtub
CW	Clothes washer
D	Number of trace days
DW	Dishwasher
$E[x]$	Expected value of x
F	Faucet
gpm	Gallon per minute
H, h	Number of homes
K, k	Fixture group
KF	Kitchen faucet
LF	Laundry faucet
M	Number of pulses
N, n	Number of fixtures (Identical or Total)
p	Probability of fixture use
psi	Pounds per square inch
P_0	Probability of zero busy fixtures
q	Fixture flow rate
$Q_{0.99}$	99th percentile of demand flow
SH	Shower
t	Average duration of water flow
T	Average duration between successive fixture operations
T	Fixture observation window
$Var[x]$	Variance of x
WC	Water closet (Toilet)
x	Number of busy fixtures
z	Standard normal distribution frequency factor
$z_{0.99}$	99th percentile of the standard normal distribution

Greek Notations

α	Percentile of the standard normal distribution
β	Weighting factor
Σ	Summation operation
Π	Product operation

Executive Summary

This study aimed to develop a statistical probability model to predict the peak instantaneous water demand for single and multi-family dwellings with high-efficiency plumbing fixtures. Using a residential end-uses of water database created by Aquacraft, Inc., fixture and appliance flow rates, and frequency of use patterns were determined and implemented in statistical algorithms to determine peak water demand. The database included fixture use and flow details from over 1000 single-family homes surveyed between 2006 and 2011 (some Colorado homes were surveyed in 1996). Standard residential indoor fixtures monitored include toilets, showers, bathtubs, faucets (including kitchen and lavatory faucets), dishwashers, and clothes washers. The database could also distinguish the efficiency levels (inefficient, efficient, ultra-efficient) for toilets, showers, dishwashers, and clothes washers.

The results of and recommendations for the end use of fixture and appliance flow rates are found in Table 10. The probability of fixture use results are found in Tables 8 and 9. The algorithms used in developing the probability model are discussed in Parts 6 and 7. Examples showing the application of the model are shown in Appendix B when sizing the water supply system. MS Excel was used to create a spreadsheet, registered as the Water Demand Calculator® (WDC), to estimate peak water demand when sizing the water supply system for single and multi-family dwellings. Fixture flow rates were determined by the average flow pulse recorded by the data loggers, which is the ratio of the total volume of water used at the fixture to the total duration of water flowing at the fixture. This expresses a duration-weighted average of all pulses at a given fixture.

Fixture use probabilities were determined by observing the peak hour of water use. The peak hour of water use was determined from the observed flow pattern as the single hour with the highest average volume of water used in the building. The probability that a fixture is busy is the percentage of time water flows from a fixture during a set observation period. The fixture observation time considers the number of days water flow was monitored in each household and the number of identical fixtures in the building. The underlying assumption is that each identical fixture has an equal probability of use irrespective of the location within a building.

Having established fixture *p*-values and fixture flow rates, a formula developed by Robert Wistort using the normal approximation to the binomial distribution was used to calculate the water supply demand for different types of fixtures. Wistort's method does not use fixture units; instead, it is a direct analytic method to calculate peak demand. However, this method was still based on congested use and is not suited for smaller systems such as single-family homes where the number of plumbing fixtures is small, and the probability of fixture use is slight.

A method called Exhaustive Enumeration was used for smaller systems with uncongested fixture use. This runs on macros in MS Excel and can numerically generate all possible combinations of the water demand from busy fixtures at any point in a building. Exhaustive Enumeration involves identifying and ranking all possible demand events for a given premise plumbing configuration. This was later replaced by a convolution method that similarly identifies and ranks the possible combinations of busy fixtures but works more efficiently in MS Excel.

A transitional method was needed between convolution and the Wistort method as the number of fixtures increased and approached congested use. A modification of the Wistort method using a *Zero-Truncated Poisson Binomial Distribution* (ZTPBD) was used for mid-range applications. This method is a bridge between the Wistort method for large buildings and the convolution method for small private dwellings.

Specific *p*-values and recommended design *q*-values are included in the WDC for single and multi-family residential dwellings having efficient plumbing fixtures.

[1] Introduction

1.1 Background and Significance

The probabilistic method for determining peak water supply demand in building plumbing systems originated from the National Bureau of Standards publication in 1940, Methods of Estimating Loads on Plumbing Systems BMS65. This method, commonly known as "Hunter's Curve," is a design curve using fixture units to determine the peak demand flow rate. As early as 1974, a US Commission identified the foremost national research priority for water supply within buildings as the need for a long-range program to develop an improved computational method for designing and evaluating water service and distribution systems in buildings. Studies have confirmed that in most building types, the application of Hunter's method results in system over-design. The problem of excessiveness was further exacerbated since the Energy Policy Act of 1992 (EPACT) required fixture flow reductions along with other conservation efforts by the WaterSense program of the U.S. Environmental Protection Agency (EPA).

One reason why the Hunter method overestimates peak demand is because plumbing fixture and appliance specifications have changed. Current household plumbing fixture specifications and use patterns need to be identified since the probabilistic method uses mathematical parameters such as the fixture flow rate, the flow duration at a fixture, and how often the fixture is in use. These fixture specifications and use patterns have significantly changed since the original Hunter method.

A second reason Hunter's method overestimates peak demand is the absence of congested use of fixtures in residential dwellings. The original Hunter model assumed congested use based on the premise that a queue of people was waiting to use each fixture. This assumption does not apply to single-family dwellings.

A third reason is that Hunter's method uses the binomial distribution and the weighting of fixtures to a unit of scale, which is accurate within the range of 150 to 300 gpm. This would require a large number of plumbing fixtures within single and multi-family homes to have a peak demand within that range. A new computational method is needed for situations with few fixtures, like a single-family dwelling.

The peak water demand study originated with IAPMO during the development of the Green Plumbing & Mechanical Code Supplement (GPMCS) in 2010. A pipe-sizing task group was one of the many task groups that functioned when creating this code supplement. The task group considered the problem of efficient and timely hot water delivery to the end user. It was expected that reducing the hot water pipe size would increase the flow velocity, reduce the volume of water in the pipe, and hence, deliver the hot water to the user quickly and with less waste. Additionally, reducing the pipe sizes was expected to reduce excess material used in construction and reduce the project's overall cost.

In 2008, the Task Group received a draft report on a revision of Hunter's curve (Cole, 2008) for efficient plumbing fixtures that led to considering the pipe sizing question from a revisionist point of view. The investigation began with revising the assumptions and parameters of Hunter's demand estimate model, which would result in a new design curve method and pipe size reduction.

A mission statement was developed that charged the IAPMO Pipe Sizing Task Group to investigate if significant water, energy, and construction cost efficiencies can be achieved by revising the method of estimating the water demand load to be provided for the water distribution system comprising the water service, cold-water distribution, and hot water distribution, and to re-evaluate the minimum required pipe sizes accordingly. If so, this Task Group would publish a detailed report of findings that would be used as the basis for code change proposals to the Uniform Plumbing Code that will help to achieve these efficiencies while ensuring continued system efficacy, performance, and safety.

In July 2011, IAPMO and the American Society of Plumbing Engineers (ASPE) convened a special task force to revise the methodology for right-sizing of plumbing systems in response to the increased use of high-efficiency plumbing fixtures, fixture fittings and appliances and the subsequent decreased demand for water in commercial buildings and residences. In collaboration with IAPMO and ASPE, the Water Quality Research Foundation (WQRF) co-founded the research project. The pipe sizing task group was reorganized with three members from ASPE who specialized in statistics and mathematics. Researchers from the University of Cincinnati with expertise in stochastic modeling of instantaneous fixture-level demand joined this effort.

1.2 Scope of Work

The pipe sizing task group recognized that statistical data was a prerequisite for any investigation toward developing a probability model to predict peak demands based on the number and kinds of plumbing fixtures installed in one system. The task group-initiated talks with Aquacraft, Inc. to access the most extensive U.S. database containing residential end uses of water surveys (REUWS), and with sponsorship, contracted a specially designed database containing parameters to determine fixture use probabilities. Since the dataset only provided water use data for residential end use, the scope of work was narrowed to single and multi-family residential dwellings.

Since today's water supply flow rate to plumbing fixtures is significantly less than that used in developing the original Hunter's curve, the scope of the work was also narrowed to indoor water-conserving plumbing fixtures. Residential efficient fixtures considered in the database are toilets, showers, dishwashers, clothes washers, and faucets (kitchen and lavatory). Bathtubs are not considered highly efficient since low-flow tub spouts have no design benefits.

1.3 Task Group Objective

The task group's objective was to develop a statistical probability model to predict the peak water demand for single and multi-family dwellings with high-efficiency plumbing fixtures. The database was queried to find probabilities of fixture use, peak hours of use, fixture flow rates, and efficiency levels using various sample selections to meet this objective. The task group would also need to develop statistically sound methods of estimating peak demands based on the insights from the datasets provided.

A benefit of this study may be that significant water, energy, and construction cost efficiencies would be achieved by implementing the developed method of estimating the peak water demand and re-evaluating the minimum required pipe sizes accordingly.

The task group's effort was narrowed to developing a statistical model that estimates peak water demand for residential dwellings. Pipe sizes are expected to decrease (compared to current plumbing codes), where the demand estimates have been reduced (compared to current codes), especially at the water supply source and water meters. A new model to estimate peak demand also requires standard hydraulic calculations for pressure losses due to friction, head loss, and velocity for accurate pipe sizing. The model plumbing codes and plumbing engineering handbooks contain procedures to perform such calculations. This study defers to standard engineering practices for hydraulic calculations to size pipe, which will be shown in the examples provided. The single outcome of this study is the development of a statistical model to estimate peak water supply demand for residential dwellings with low-flow fixtures.

[2] Literature Review

The task group collected a large array of literature dealing with computational methods for estimating water demand in buildings. Beginning with the post-World War I conservation era spurred by President Warren G. Harding and Secretary of Commerce Herbert Hoover in 1921, a proliferation of scientific investigations was published by the National Bureau of Standards (NBS) for the building and housing industry for the next four decades (Cole 2009). One of the most significant NBS publications for the plumbing industry was a report by Dr. Roy B. Hunter on Methods of Estimating Loads in Plumbing Systems (Hunter 1940). This report explained how the binomial distribution function was applied to different plumbing fixtures to estimate peak demand for any plumbing system.

This method of estimating peak water demand in buildings is still dominant in the United States and is known as Hunter's curve. Dr. Hunter determined the probability that a particular fixture will be in operation as $p = t/T$, where t is the average duration of water flow in seconds, and T is the average time between successive operations in seconds. The binomial distribution function describes the probability of simultaneous operation of fixtures out of a total number of fixtures, and this analysis was used to determine the maximum number of fixtures that will operate within the 99th percentile. The probability and flow rate for various types of fixtures were used to determine a weighted average for each fixture type, and this weighted average was expressed in "fixture units," a term coined by Hunter (Cole 2008). In practice, the designer adds all the fixture units being served by a plumbing system, and the fixture unit total is converted to a flowrate (gpm) by using a graphical curve showing the relation between number of fixture units and flowrate from which the appropriate pipe size can be determined.

The Hunter method is limited by the applicability of the assumption of congested conditions of service, which is defined as the maximum practical rate at which fixtures can be used continuously in actual service. In other words, the analysis employed by Hunter assumes a queue of people are waiting to use each fixture. While valid in certain applications where there is a line of people waiting to use the facilities, the assumption is not valid in applications such as residential buildings, especially single-family homes. This limitation has been a source of criticism of the pipe sizing method in the plumbing codes, where Hunter's method is invalid because of the assumption of congested use.

Plumbing research continued at the National Bureau of Standards in the 1950s and 1960s. In 1962, the United States organized the U.S. National Committee for the International Council for Building Research (USNCCIB) as a counterpart commission to participate in the International Council for Research and Innovation in Building and Construction (CIB). CIB was established in 1953 with the support of the United Nations to stimulate and facilitate international collaboration and information exchange between government research institutes in building and construction. In 1971, a CIB Commission on Water Supply and Drainage for Buildings (CIB W062) was established, and a US counterpart commission was established in 1973. The first position paper published by the US counterpart commission (USNCCIB 1974) identified the foremost national research need for water supply within buildings, namely, a long-range program to develop an improved computational method for designing and evaluating water service and distribution systems in buildings. Studies have confirmed that in most building types, the application of Hunter's method results in excessive over-design of the system.

From 1971 to now, CIB W062 has spawned voluminous papers with significant attention toward computational methods to resolve the Hunter method problem. Thomas P. Konen, an original member of the U.S. counterpart commission, contributed substantially to the national need for an improved Hunter method. Over 20 years, Konen published articles and papers demonstrating a modified Hunter model (Konen and Brady 1974; Konen et al 1976; Konen and Chan 1979; Konen 1980; Konen 1989; Konen 1993; Konen 1995). In 1983, the BOCA Plumbing Code adopted the first major revision of the Hunter method since 1940 based on the proposed modifications of Konen (Galowin 1983). In 1995, the National Standard Plumbing Code adopted further revisions forwarded by Konen based on the performance of low-consumption fixtures (Wagner 1994).

The initial international response to a Hunter re-evaluation came from the United Kingdom, Japan, Brazil, and Sweden (Konen and Gonclaves 1993). The computational approaches to determine the design flow rate forwarded by these countries can be categorized as probabilistic or simulation. The probabilistic approach employed a binomial distribution and Poisson distribution based on queuing theory, and the simulation approach employed the Monte Carlo method. Later developments from Brazil employed Fuzzy Logic (Oliveira *et al*. 2009; Oliveira *et al*. 2010), and the Netherlands developed SIMDEUM, a stochastic model based on end-use statistical information (Pieterse-Quirijns *et al*. 2012).

Outside of the CIB international network, the re-evaluation of Hunter's method has been published in the Journal of American Statistical Association (Connor and Severo 1962), the Journal of American Water Works Association (Chan and Wang 1980), ASHRAE Handbook (ASHRAE 1987), Plumbing Engineer (Konen 1980; Breese 2001), and the Journal of Pipeline Systems Engineering and Practice (Mazumdar *et al*. 2013).

At the 1994 ASPE Convention, Robert A. Wistort presented a paper, "A New Look at Determining Water Demand in Buildings: ASPE Direct Analytical Method" (Wistort 1995). In this publication, Wistort describes a procedure for an analytical approach that uses a normal distribution to approximate the binomial distribution that occurs naturally from the "on or off" nature of plumbing fixtures. This approximation is valid when n, the number of fixtures, is large, and the approximation becomes questionable when n is small. Wistort's approach is advantageous in eliminating the need for fixture units. While the concept of fixture units was a clever way for Hunter to combine the flow characteristics of different types of fixtures, it has the disadvantage of being a rough approximation. As discussed in Section 6 of this report, Wistort's direct analytic method was selected as the foundational model for developing a new computational model applicable to residential dwellings.

Up to this point, estimates of indoor water demands were needed mainly for design purposes. In particular, peak water demand is the key factor governing the size of the premise plumbing supply system for a building. In the 1990s, indoor water demands gained new importance for operational purposes. The passage of the federal Safe Drinking Water Act in 1974 and its Amendments in 1996 spurred the development of mathematical models to generate stochastic water use patterns at the fixture level. These patterns were needed to drive emerging computer programs like EPANET that simulate changes in hydraulic and water quality conditions during the operation of a municipal pipe network.

Toward this end, researchers at the University of Cincinnati developed and tested a Poisson rectangular pulse (PRP) model to simulate instantaneous water use at the household fixture level (Buchberger and Wu, 1995; Buchberger and Wells, 1996; Buchberger *et al*., 2003; Buchberger and Li, 2007). The PRP model is a dynamic stochastic companion to the static binomial model used by Hunter to describe the probability distribution of busy fixtures. Besides its use as an operational tool for network simulation, the PRP model has other versatile applications for premise plumbing design. For instance, the PRP framework formulated a frequency factor approach for estimating instantaneous peak indoor water demands (Zhang *et al*., 2005; Buchberger and Zhang, 2005). The PRP frequency factor approach is identical in principle to the direct analytical method proposed by Wistort. In addition, Buchberger *et al.* (2008) used the PRP framework to demonstrate a reliability-based approach for estimating peak indoor water demands and then identifying the corresponding pipe size needed to achieve daily self-cleaning operations.

[3] Residential Water Use Database

3.1 National Survey

The data needed to investigate the development of a new probability model to predict peak demands was collected and provided by Aquacraft Inc. The database consists of water use measurements taken between 1996 and 2011 from over 1,000 single-family homes across the United States. The water use data were recorded with a portable data logger connected to each home's main water supply pipe. The data logger recorded the volume of water flowing through the main pipe every 10 seconds. The recorded flows were analyzed by Aquacraft using their proprietary Trace Wizard© software and disaggregated into individual water use events. Each water use was associated with one of three mutually exclusive household draws: indoor fixtures, outdoor fixtures, or leaks. Only indoor fixture use is considered in this study.

The water use data was stored in MS Access format to facilitate queries. As shown in Table 1, the database contained two types of information, namely (i) household survey data and (ii) measured flow data. The household survey data reflect characteristics of the home, the residents, and the water fixtures; the measure flow data describe the duration, volume, and number of water use events at each fixture group identified in the home. The maximum data-logging period at each home was 14 days. To capture the diurnal variation in indoor residential water use, results for each fixture in each house were summarized on an hourly basis.

Table 1: Survey and Measured Water Use Data in the MS Access Database

Household Survey Data	Measured Flow Data
- Number of residents and age distribution	- Number of fixture-use events
- Type of fixtures	- Duration of each fixture use event
- Number of each fixture type/group	- Volume of each fixture use event
- Number of renovated or retrofitted fixtures	- Daily observed fixture peak flow
- Number of bedrooms and bathrooms	- Logging dates

The distribution of the 1058 surveyed households is summarized in Table 2. A small percentage (2%) of homes was dropped from the analysis due to vacations or other conditions that gave zero or minimal water use. The remaining 1038 homes had a total of 2,821 occupants who generated nearly 863,000 water use events during 11,385 home-days of monitoring. On a per-household basis, this translates to an average of 11 trace days per home, 2.72 residents per home, and 28 and 831.4 water use events per capita and home, respectively. Figure 1 illustrates the geographic location of the 1038 homes that participated in the national water use survey conducted by Aquacraft during the period 1996 to 2011.

Table 2: Homes Surveyed

Location by State	Number of Homes	Number of Occupants	Survey Years
Arizona,AZ	17	41	2007 - 2009
California,CA	447	1326	2006 - 2009
Colorado,CO	206	533	1996, 2007 - 2010
Florida,FL	32	78	2007 - 2009
Kentucky,KY	58	128	2007
Nevada,NV	20	593	2007 - 2009
New Mexico,NM	237	44	2010 - 2011
Oregon,OR	24	66	2007 - 2009
Utah,UT	17	56	2007 - 2009
Responded to survey	1058	2865	-
Invalidated homes	(20)	(44)	-
Analyzed Total	1038	2821	-

Figure 1: Homes from 62 Cities in Nine States Participated in the National Water Use Survey

3.2 Exploratory Data Analysis

Six unique fixture groups were common to most of the 1038 participating homes (see Table 3). The database does not differentiate between kitchen and lavatory faucets; therefore, both are included in the fixture group "faucet". Water use falling outside these six categories was lumped into "Other". For instance, some homes had evaporative coolers, water treatment devices, or unknown fixtures. The total volume of water used at each fixture differs due to the fixture function and frequency of use. Table 4 is a breakdown of the average water use per capita in 1038 households. Toilets had the highest average volume of water consumed in gallons per capita per day (GPCD), while dishwashers had the lowest use. The mean daily water use was 60.09 GPCD (72.07 GPCD, including leaks).

Table 3: Six Fixture Groups Common to Most Homes

Fixture Group	Abbreviation	Number of Homes	Number of Fixtures	Average Fixtures per Home
Bathtub	BT	519	852	1.64
Clothes Washer	CW	1002	1002	1.00
Dishwasher	DW	722	728	1.01
Faucets	F	1038	4013	3.87
Shower	SH	1014	2132	2.10
Toilet	WC	1037	2502	2.41

Table 4: Average Per Capita Frequency and Volume of Water Use at 1038 Single-Family Homes

Fixture	Water use events (per capita per day)	Volume (Gallon per capita per day)
Bathtub	0.08	1.54
Clothes Washer	0.97	14.31
Dishwasher	0.33	0.77
Faucet	22.74	11.87
Shower	0.76	12.59
Toilet	5.80	15.18
Others	9.74	3.84
Leaks	50.11	11.98
Totals (excluding leaks)	40.42	60.09

Each recorded water use event at a fixture has a corresponding flow duration and volume. The relative fixture use was determined as a percentage of the total measured water use data. Over 2.5 million water use events were recorded. Table 4 shows that daily water use attributed to leaks accounted for over 50% of the daily water use events, about 17% of the volume (Figure 2), and about 70% of the time water flowed. However, the average flow rate of leaks was less than 1% of the demand compared to the six fixture groups identified in the database (see Table 6). Water use events were classified as “leaks” if the event could not be attributed to a specific fixture group, given the timing, duration, frequency of occurrence, and flow rate. Nearly 98% of the homes registered some leak. Of the homes with leaks, 58% had leaks under 10 gallons per day (gpd), while 5% had leaks exceeding 100 gpd. The mean observed leak in a home was 27.2 gpd with a standard deviation of 79.3 gpd. Although leakage accounted for nearly 17% of the volume of daily water use, leaks are not a design factor and, hence, are not considered further in this study.

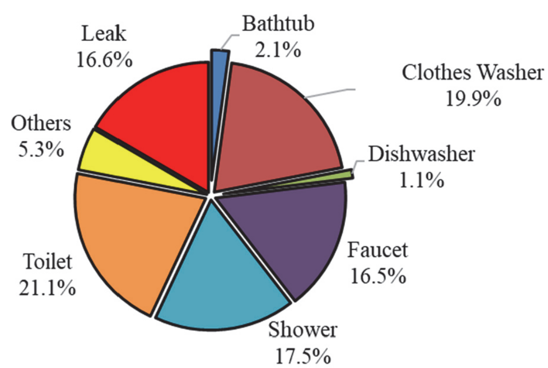


Figure 2: Relative Distribution of Daily Per Capita Volume of Water Use at 1038 Residential Households

Figure 3 illustrates the relative distribution of water use at the different fixtures. Faucets had the highest percentage of water-use events at about 75%, with a 21% volume of water consumed. In contrast, showers and clothes washers recorded less than 3% each of water-use events but accounted for about 24% each of the volume of water consumed. Toilets had the highest volume of water consumed at a fixture, while dishwashers had the lowest number of events and volume of water consumed. Although the number of water-use events shows a wide variation in the frequency of fixture use, the duration and flow volume are consistent with typical residential fixture characteristics.

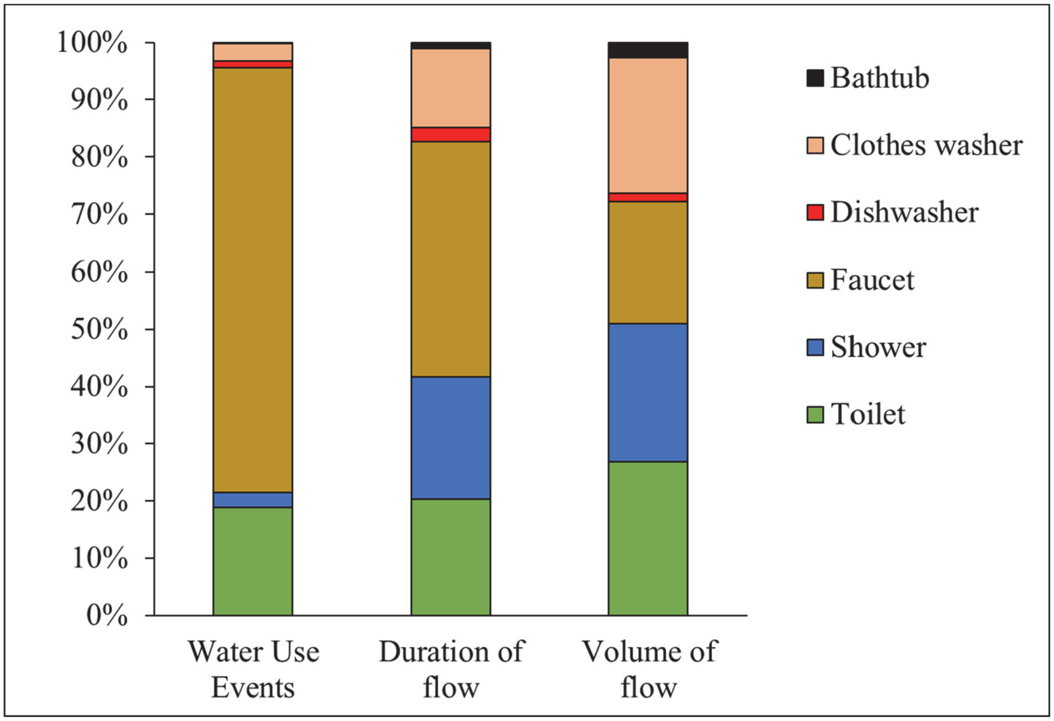


Figure 3: Relative Distribution of the Measured Fixture Flow Data at 1038 Households

3.3 Fixture Classification

Four of the six common fixtures were classified as either ultra-efficient, efficient, or inefficient based on their average volume of water consumed per use or their average fixture flow rate. The criteria for each classification and sample size are shown in Figure 4. Bathtubs and faucets are not classified based on efficiency because their intensity, duration, and volume of water use depend on the user.

The surveyed homes had common fixture groups with a wide variety of observed flow rates, duration of use, and volume from each fixture group (See Appendix A Figures A4-A8 and Table A1). Bathtubs had the highest average fixture flow rate, while ultra-efficient dishwashers had the lowest average flow rate. Within the three fixture groups classified according to volume-based efficiency (see clothes washer, dishwasher, toilet in Figure 4), the fixture average flow rate increased as the fixture efficiency decreased. Similarly, the average volume of water consumed per fixture per capita per day increased for all fixture groups as the efficiency of the fixtures decreased. A summary of the exploratory data analysis based on fixture efficiency (i.e., fixture duration per use, volume per capita per day, and flowrate) can be found in Appendix A, Table A1.

3.4 Fixture Flow Characteristics

Water use at a fixture generates a flow pulse. To illustrate, Figure 5 shows three hypothetical water use events at a household fixture during a 1-hour window. The pulse duration is exaggerated. The area of the pulse represents the volume of water used. The pulses on the left side of Figure 5 have unsteady intensities to signify what the data logger may observe. In the middle are the idealized equivalent rectangular pulses derived by setting flow rates at the intensity needed to preserve the observed pulse's volume and duration. Two pulses can occur from identical fixtures during the monitoring window. Portions of both pulses overlap, signifying two similar fixtures operated simultaneously for a brief time in the home. During this period of concurrent water use, the total flow into the house is the sum of the flow rates at the two individual fixtures. The average flow pulse on the right side of Figure 5 describes the flowrate calculated for each water-use event at a fixture.

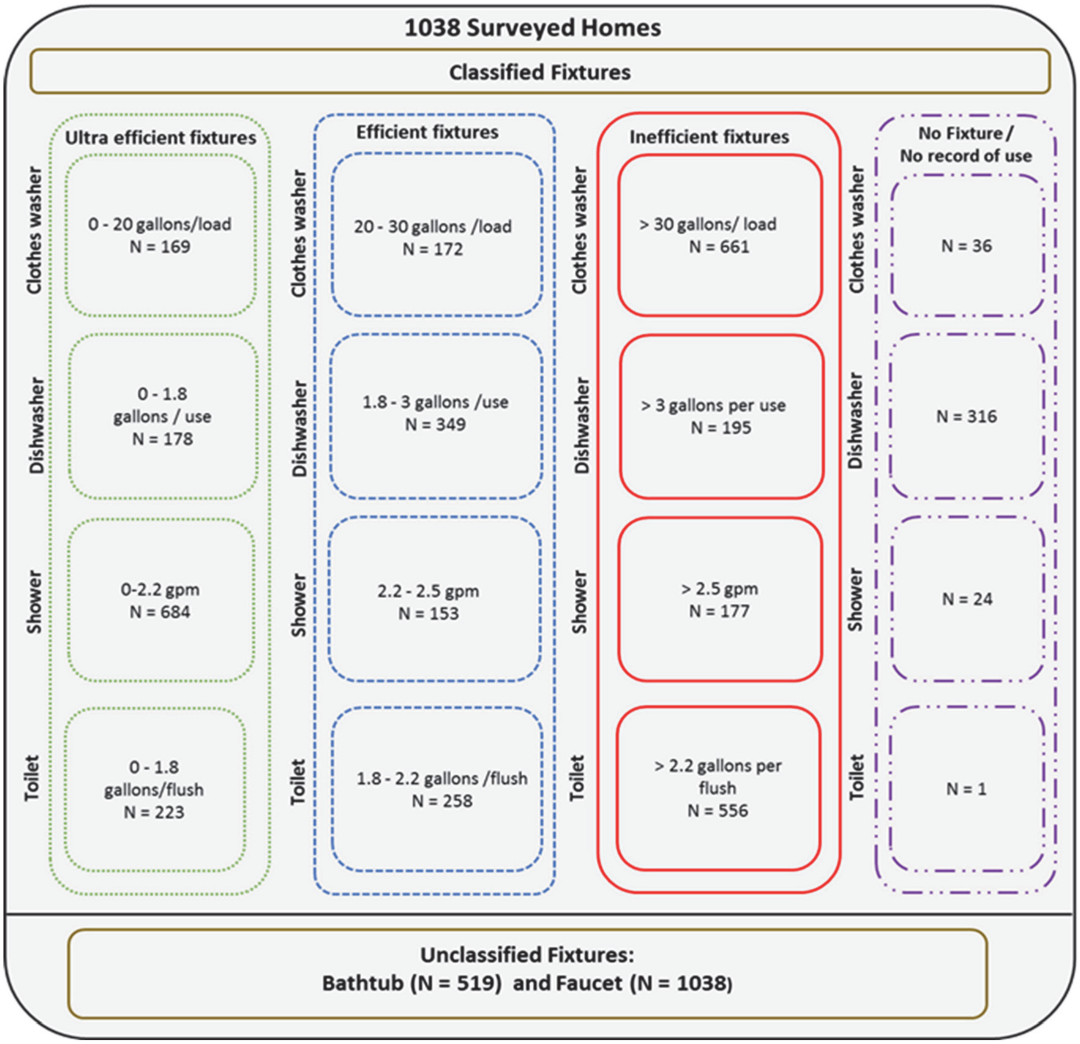


Figure 4: Fixture Efficiency Criteria and the Sample Size Within Each Group

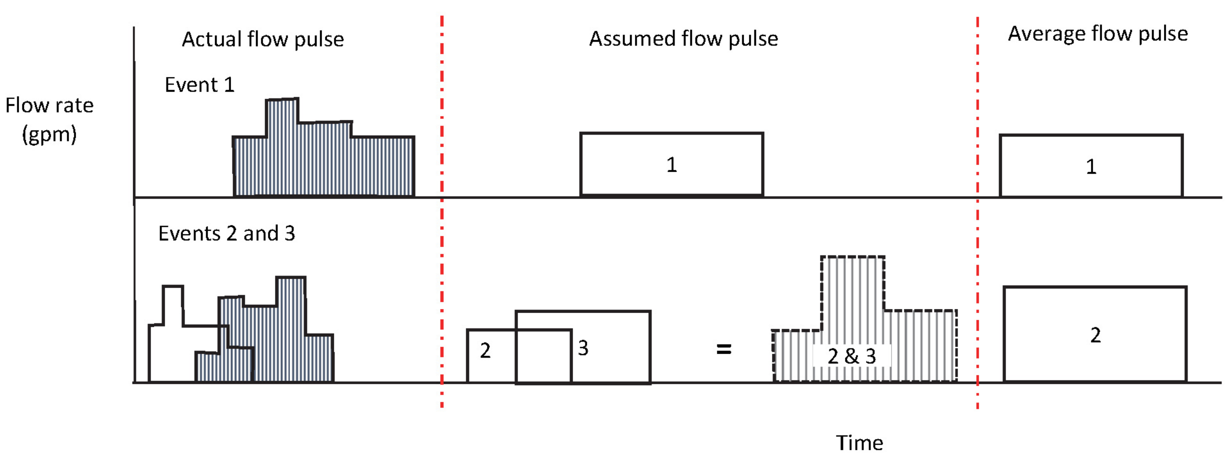


Figure 5: Illustration of Actual and Assumed Flow Pulses for Three Water Use Events

Due to variations in system pressure, differences in fixture settings, idiosyncrasies in user habits, and many other factors, the intensity of the rectangular water pulse may vary from use to use at the same fixture. The average rate of flow resulting from water use at a fixture group in a home is computed as the ratio of the total volume consumed at the fixture to the total duration of time water was flowing at the fixture or

$$Average\ flow\ rate = \frac{Total\ volume\ of\ water\ used\ at\ fixture}{Total\ duration\ of\ flowing\ water\ at\ fixture} \quad [3.1]$$

This expression is a duration-weighted average of all pulses at a given fixture. To illustrate, Figure 6 depicts graphically how Equation 3.1 obtains the average flow rate for the five pulses at a fixture. The dashed line is the average flow rate of pulses. An example calculation based on Equation 3.1 for the average flow rate of the five pulses shown in Figure 6 is presented in Table 5.

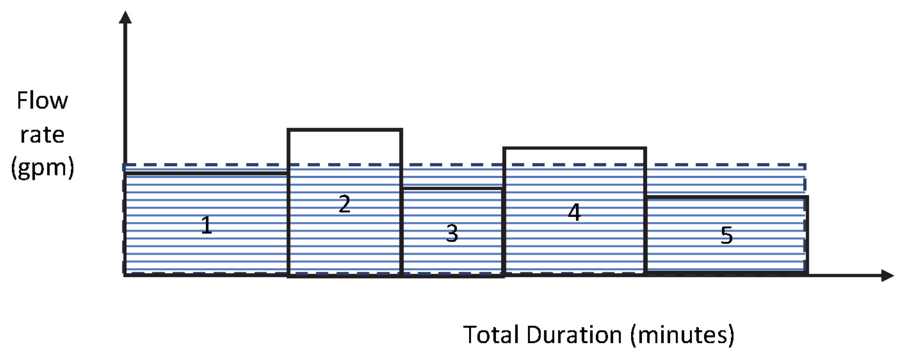


Figure 6: Example Showing the Average Flow Rate of Five Pulses

Table 5: Example Calculation for Average Flow Rate for the Five Pulses Shown in Figure 6

Pulse Number	Pulse Intensity (gpm)	Pulse Duration (minutes)	Pulse Volume (gallons)
1	1.81	8.8	15.93
2	2.25	5.7	12.82
3	1.76	4.9	8.62
4	2.05	7.8	16.00
5	1.55	9.1	14.10
Total		36.3	67.47
Average Flow Rate at Fixture		67.47 gallons / 36.3 minutes = 1.86 **gpm**	

Following the flow rate calculation method described in this section, the fixture flow rates were queried from the national database for all the fixture efficiencies, as classified in Figure 4. Figure 7 shows the distribution of measured flowrates for all fixtures at all efficiencies. All fixtures had maximum and minimum flowrates as outliers (top and bottom 10%), and the average fixture flow rate increased with reduced fixture efficiency. Table 6 summarizes the national database's measured average flow rate for efficient fixtures.

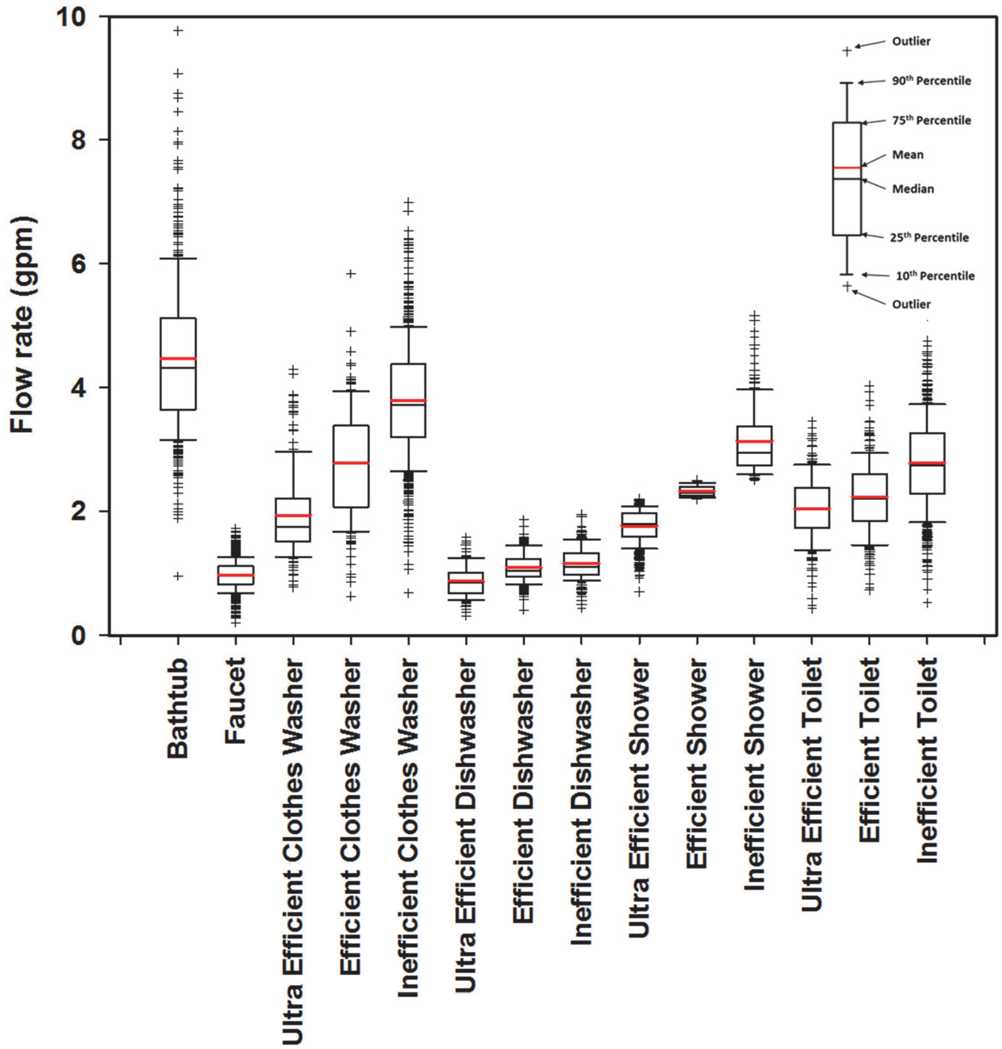


Figure 7: Box and Whisker Plot of Flow Rate for the Different Efficiency Levels of Fixtures

Table 6: Calculated Water Use for Efficient Fixtures in 1038 Single-Family Households

Fixture	Average Flow Rate (gpm)
Bathtub	4.39
Clothes washer	3.06
Dishwasher	1.03
Faucet	0.93
Shower	2.01
Toilet	2.38
Others	0.11
Leak	0.08

Other water use characteristics computed for each of the six fixture groups include the average volume per use and average duration per use, given by Equations 3.2 and 3.3, respectively,

$$Average\ volume\ per\ use = \frac{Total\ volume\ of\ water\ used\ at\ fixture}{Total\ number\ of\ times\ fixture\ was\ used} \quad [3.2]$$

$$Average\ duration\ per\ use = \frac{Total\ duration\ of\ flowing\ water\ at\ fixture}{Total\ number\ of\ times\ fixture\ was\ used} \quad [3.3]$$

Note that the ratio of Equation 3.2 to Equation 3.3 also gives the average flow rate at the fixture group, as defined in Equation 3.1. The results from these calculations and other statistical properties of indoor residential water use at the fixture groups are summarized in Appendix A.

3.5 Peak Water Use Analysis

In a 24-hour window, water use in residential buildings usually presents as a diurnal pattern, having morning and evening peak periods. These peak periods represent activities such as waking up, preparing to leave the house, returning home from work or school, and preparing to retire at night for the occupants in the building. Sometimes, the peak period may vary in time and intensity due to the occupant age group, work shift, and day of the week. The peak water use is from a combination of all the fixture use events in the building.

A peak period of water use in a building can be defined as either the hour of maximum water consumption or the hour with the highest number of water use events for all the fixtures in the building. These two conditions often occur at any given home during the same hour, but their joint occurrence is not assured. The database was examined to find the hour of peak water use according to both definitions at all 1,038 homes. There was no distinction between weekdays and weekends. In the database, each fixture group had a different peak use hour. Shower and toilets had peak use in the morning from 6-8 a.m., clothes washers peaked in late morning, bathtub and faucet use peaked in the early evening from 5-6 p.m., while dishwasher use peaked from 8-9 p.m.

Figure 8 shows a similar diurnal pattern of peak water use for the volume and the number of events. As expected, many homes experienced morning or evening peak hours. Surprisingly, each hour of the day is represented at least once in Figure 8. This means there is at least one residence in the database where the hour of peak water use is, for example, consistently at 1 a.m. The 4-hour interval from 6:00 to 10:00 a.m. consists of about 50% of the peak hours by volume and 42% by number of events. The morning rush hour from 7:00 to 8:00 a.m. is the most likely time to experience the hour of peak water use, both by volume and by number of uses.

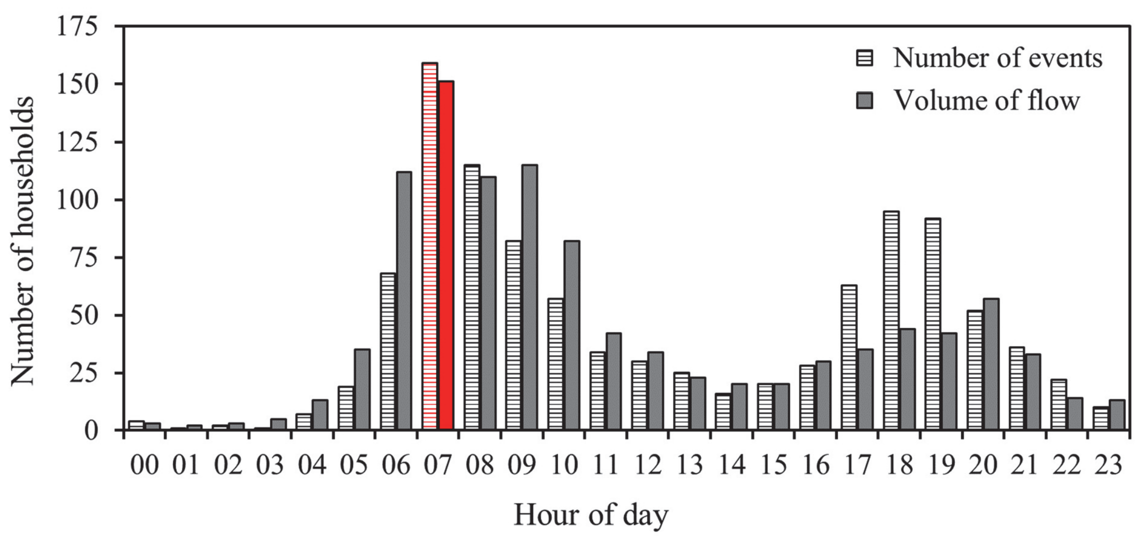


Figure 8: Distribution of Observed Peak Hour of Water Use in 1,038 Single-Family Households

The hourly volume of water consumed in a building varies, with a high volume of water consumed when the occupants wake up for a new day or return from work and school and a low volume of water consumed when residents are sleeping or away from home. The peak hour of water use is determined from the observed flow pattern as the single hour with the highest average volume of water use in the building (*e.g.,* hour 07 in Figure 9). The possibility that all the fixtures in a building would be busy simultaneously is improbable; however, the design of building water demand should represent water use expected during the peak hour.

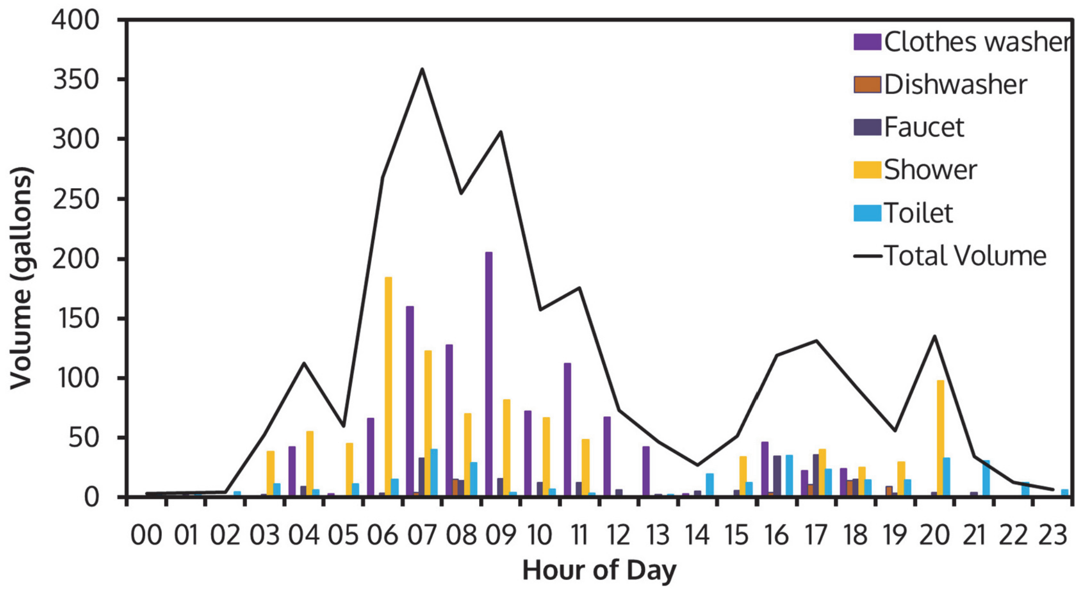


Figure 9: Observed Hourly Water Use in a Single-Family Residence Over 2 Weeks

3.6 Main Assumptions

The following are some key assumptions that were made in the analysis of the water use data:

1. The flow pattern for a single water use event at any fixture is a rectangular pulse described by two parameters: a constant flow for a fixed duration.
2. Fixtures with identical functions have the same probability of use, irrespective of their location in a building.
3. The kitchen sink and bathroom lavatory are considered to be faucets with identical water use signatures.
4. The existing plumbing system in each home of the database is appropriately designed and operated within typical residential norms.

[4] Estimating Fixture Design *p*-values.

4.1 Single Home Fixture Probability of Use

A water fixture has two states. It is either on (running water) or off (not running water). When a fixture is "on," it is said to be busy; one that is "off" is said to be idle. An excellent relative frequency estimate of the probability that a fixture is busy is given by the percentage of time that water is flowing from that fixture during an observation period. To illustrate the basic idea, consider Figure 10, which shows the duration of two water use events at a fixture (t_1 and t_2) during an observation window of duration *T*. In this case, the probability *p* of a busy fixture is given by,

$$p = \frac{t_1 + t_2}{T} \qquad [4.1]$$

To account for homes with multiple identical fixtures and a continuous data logging period of up to two weeks, the general expression for estimating the hourly busy fixture probability becomes

$$p = \frac{t_1 + t_2 + \cdots + t_M}{NDT} \qquad [4.2]$$

Here, *M* is the total number of water use pulses attributed to a given fixture group with *N* identical fixtures in a single home monitored for a period of *D* complete days. Equation 4.2 reduces to the simple example of Equation 4.1 if *N* = 1, *D* = 1, and *M* = 2. Since residential water use has substantial diurnal variability (Figure 9), each day was divided into 24 one-hour observation windows (hence, *T* = 60 minutes), the peak hour by volume was identified, and the probability of fixture use was calculated using Equation 4.2.

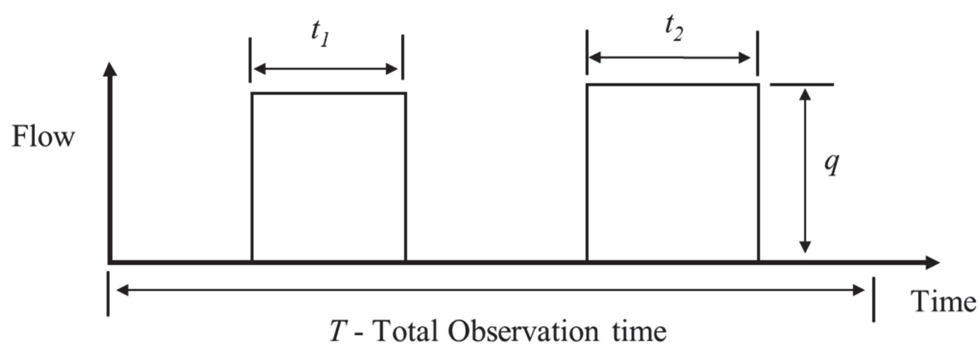


Figure 10: Time Intervals Needed to Estimate the Probability of a Busy Fixture

4.2 Group of Homes Fixture Probability of Use

The results in section 4.1 give the hourly probabilities of busy fixture use in a single home. The water use database contains hundreds of homes with different fixture counts, monitoring periods ("trace days"), and, hence, different hourly *p* values. How should these *p* estimates from single-family homes be combined to provide a representative value?

Homes were grouped by their number of occupants. To illustrate, suppose there is a group of *H* homes with three occupants, each monitored for a common time *T*. The corresponding representative hourly value of *p* from *h* independent estimates of the probability of fixture use in this category is given by,

$$\bar{p} = \sum_{h=1}^{H} \beta_h p_h \qquad [4.3]$$

where β is a dimensionless weighting factor, $\beta_h = \frac{N_h D_h T_h}{\sum_{h=1}^{H} N_h D_h T_h} = \frac{N_h D_h}{\sum_{h=1}^{H} N_h D_h}$.

The weighting factor gives a greater influence on probability estimates from homes having higher "observation opportunities" (*i.e.*, more fixtures or more trace days). The example in Table 7 shows how the weighted average probability of a morning shower (T = 60 minutes daily) is found for five homes with three occupants each. Column E shows that the single hourly estimates of p computed using Equation 4.2 range from 0.0359 to 0.0892. The single representative value is p = 0.0526, found at the bottom line in Column G. It is the weighted average of the p estimates in Column E.

Table 7: Estimating *p* for 7-8 am Shower Use in Group of *H* = 5 Homes, Each with 3 Occupants

	A	B	C	D = A*B*T	E = C/D	F = D/Sum(D)	G = E*F
Home ID, *h*	**Shower Fixture Count, *N***	**Monitor Period (days), *D***	**Duration of Busy Fixture (minutes)**	**Fixture Observation Window (minutes)**	**Hourly Probability of Fixture Use, *p* Eq. 4.2**	**Weighting Factor, β**	**Contribution to Weighted Avg Probability Eq. 4.3**
1	3	13	84.0	2340	0.0359	0.2727	0.0098
2	2	13	96.5	1560	0.0619	0.1818	0.0112
3	3	14	98.5	2520	0.0391	0.2927	0.0115
4	1	12	64.2	720	0.0892	0.0839	0.0075
5	2	12	108.0	1440	0.0750	0.1678	0.0126
Total	11	64	451.2	8580	--	1	***p* = 0.0526**

4.3 Single Family Fixture Design "*p*" Value

As illustrated in Figure 9, water use in a single-family home has a pronounced diurnal pattern. To estimate peak demand, the critical observation period is the hour of the day at each household in which the largest volume of water is used. After identifying the peak hour of water use in each household, the peak hour probability of fixture use was calculated for each fixture type using Equation 4.2. Households were grouped by their number of occupants, and the weighting scheme described in Table 7, based on the duration of the observation window at each home, was used to combine the collection of computed *p*-values into a single representative estimate for each fixture group. The representative fixture peak hour probability of use was estimated for households with 1, 2, 3, 4, and 5 or more occupants. The peak hour probability of fixture use was calculated for weekday and weekend water use.

Figure 11 shows the trends of fixture probability values for weekday and weekend water use for fixtures grouped by the number of occupants in each household. There is a significant positive correlation (α = 5%) between the peak hour fixture *p*-values and the number of occupants in a household in the case of faucets, showers, and toilets. These fixtures were the most active during the peak hour. Meanwhile, the bathtub *p*-values had a slight negative correlation, and no distinct trend was observed for the clothes washers and the dishwashers relative to the number of occupants per household.

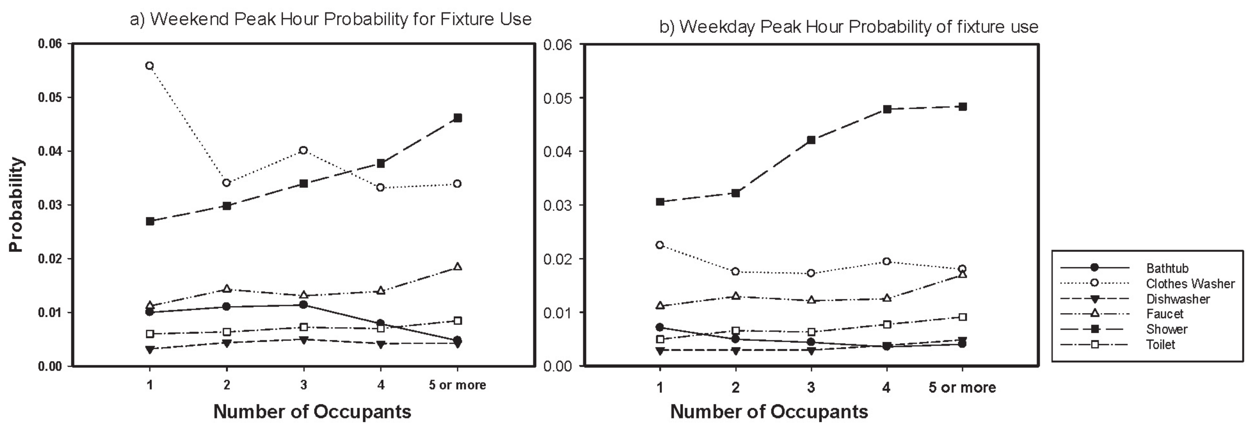


Figure 11: Peak Hour Probability of Efficient Fixture Use in Homes Grouped by their Number of Occupants for a) Weekend Water Use and b) Weekday Water Use

Figure 11 illustrates that the fixture *p*-values had a similar trend between weekday and weekend water use. However, the national database revealed that residential water use tends to be greater on weekends than on weekdays. For this reason, weekend water use data were used to identify the peak hours of water use. The resulting representative fixture *p*-values were selected as the maximum computed average *p*-value from the groups based on the number of residents and rounded to the nearest 0.005 (see Table 8).

Table 8: Design Peak Hour Probability of Use for Efficient Fixtures in a Single-Family Home

Fixture	Design *p*-value	Sample Size
Bathtub (no shower)	**0.010**	308
Clothes washer	**0.055**	296
Dishwasher	**0.005**	415
Faucet*	**0.020**	1013
Showerhead	**0.045**	790
Toilet	**0.010**	469
Tub/Shower Combination**	**0.055**	235

***** Sink for bar, bath, kitchen, and laundry

** Calculated from the probability of bathtub **or** shower in use (i.e., $p_{[Bathtub]} + p_{[Shower]}$)

4.4 Multi-Family Fixture Design "*p*" value

Although the national database had water use records for only single-family homes, it can be assumed that each unit in a multi-family building operates independently of the other units and can be represented by a single-family home. Therefore, water use data from multiple randomly selected single-family households were assembled and assumed to be units in a building to mimic water use in a multi-family building.

Like single-family homes, the number of occupants was the grouping criterion to estimate the representative fixture *p*-value in this simulation exercise. Each building with *h* units had between *h* to 4*h* or more occupants. The maximum value from the probability estimates based on the number of occupants in a building with *h* units was selected as the representative fixture *p*-value. As illustrated in Figure 12, the peak hour fixture *p*-values decreased with the increasing number of units in the building. This is because the individual units are not experiencing peak use simultaneously. Omaghomi *et al*. (2020) reported that the percentage of units experiencing peak use simultaneously with the building decreased from 100% at h = 1 to 20% at h = 20.

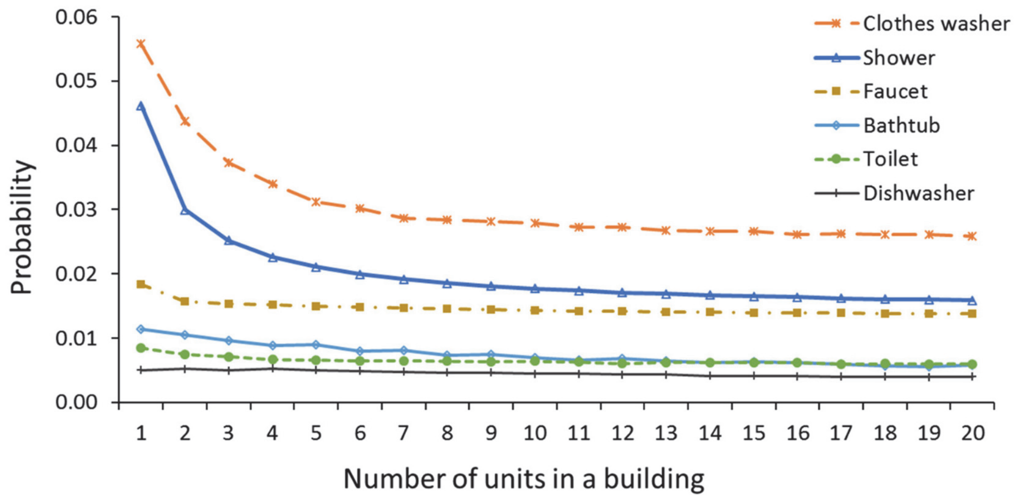


Figure 12: Simulated Fixture *p*-values in a Multi-Family Building

For ease of use, the fixture *p*-values in Figure 12 were modeled using nonlinear regression to develop a simple expression for predicting the peak hour fixture *p*-value as a function of the number of units h in the buildings. Table 9 summarizes the simple expression to estimate fixture *p*-values in multi-family buildings, showing a correlation of at least 90% between simulated and modeled *p*-values for all fixtures.

Table 9: Fixture *p*-values in Multi-Family Buildings

Fixture	$^{+}P_1$	P_h*	R^2 (Simulated vs. Model)
Bathtub	0.010	$\mathbf{1.20}\ P_1\ h^{-0.25}$	97.7%
Clothes washer	0.055	$\mathbf{0.95}\ P_1\ h^{-0.30}$	98.9%
Dishwasher	0.005	$\mathbf{1.00}\ P_1\ h^{-0.10}$	96.0%
Faucet	0.020	$\mathbf{1.10}\ P_1\ h^{-0.15}$	89.6%
Shower	0.045	$\mathbf{0.82}\ P_1\ h^{-0.30}$	99.2%
Toilet	0.010	$\mathbf{0.75}\ P_1\ h^{-0.07}$	98.6%
Tub/Shower Combination	0.055	$\mathbf{0.92}\ P_1\ h^{-0.28}$	99.1%

$^{+}$ P_1 are the values for single-family homes in Table 6

* For $h \geq 2$

[5] Estimating Fixture Design Flow Rates

Table 6 summarizes the national database's measured average flow rate for efficient fixtures. Further modification was needed when considering a maximum design flow rate for fixtures that met the criteria for water efficiency, as shown in Figure 4. Maximum design fixture flow rates are needed when estimating design flows, which will be discussed in Section 6. An upper limit to fixture flow rates is proposed to restrict the fixture flow rates to water efficiency levels already specified by fixture manufacturers at the time of this research, which is further explained below. Given the upper limit, fixture flow rates can be less than the maximum design flow rate to allow further conservative efficiency levels.

The criteria for determining the maximum design flow rates for showerheads and bathroom faucets were the EPA WaterSense Specifications, which specified their maximum flow rates at 2.0 gpm (EPA 2018) and 1.5 gpm (EPA 2007), respectively.

Flow rate data for residential clothes washers and dishwashers provided by an appliance manufacturer approximated the average flow rate shown in Table 6. There was a significant difference in water volume between the vertical and horizontal axis clothes washing machines. However, the average fill flow rate for the hot and cold between the vertical and horizontal axes did not significantly differ. The higher flow rates were seen in the vertical axis clothes washers and were used to select a maximum design flow rate of 3.5 gpm. The manufacturer's data showed an average fill flow rate for a residential dishwasher as 0.96 gpm, with the highest flow rate at 1.30 gpm. The highest flow rate was chosen as the maximum design flow rate for dishwashers.

The flow rate for residential toilets was selected based on ultra-efficient criteria in Figure 4 and EPA WaterSense Specifications for 1.28 gpf tank-type toilets (EPA 2014). The flow rate at the 75th percentile for ultra-efficient toilets, shown in Figure 7, is a little less than 3.0 gpm. A fill valve flow test report between several samples showed a fill rate between 2.4 - 2.9 gpm at 20 psi and between 3.7 - 4.9 gpm at 50 psi. The data in Figure 7 show the 90th percentile flow rate of inefficient toilets less than 4.0 gpm. In consideration of the data from the national database, the maximum design flow rate for residential toilets was selected at 3.0 gpm.

Bathtub fillers do not have an efficiency rating or flow control; their flow rates vary depending on the available pressure. The fill rate of a bathtub should have sufficient flow to the user's satisfaction. The flow rate data at the 75^{th} percentile for bathtubs shown in Figure 7 is at 5.5 gpm. The 90^{th} percentile was approximately 6.0 gpm, with outliers ranging between 6.0 gpm and 10.0 gpm. The 75^{th} percentile was chosen as a maximum design flow rate for bathtubs, recognizing that lower flow rates may be practical according to the data.

Some fixtures listed in Table 10 were not part of the database; their flow rates were added based on fixtures with comparable functions. A residential bar sink faucet has a comparable flow rate with the lavatory faucet, and therefore, 1.5 gpm was selected as the maximum design flow rate. A residential laundry faucet with an aerator can have a flow rate of 1.5 gpm or 2.0 gpm, and a higher flow rate is recommended for the maximum design flow rate. Similarly, the bidet faucet flow rate was recommended at 2.0 gpm. The combination bath/shower has two mutually exclusive water outlets. Water will flow through the tub spout or the shower head from the same fixture fitting. The recommended maximum design flow rate for this fixture fitting is based on the flow rate for the tub spout and is the same as the bathtub flow rate. Lower flow rates may be considered practical for tub fillers. Water-conserving kitchen faucets have a flow rate of 1.8 gpm with a temporary maximum flow rate of 2.2 gpm that defaults back to 1.8 gpm upon valve closure. The kitchen faucet's higher flow rate of 2.2 gpm was selected as the maximum design flow rate. A list of the maximum design flow rates for efficient fixtures in residential buildings is in Table 10.

Table 10: Design Flow Rate for Water-Conserving Plumbing Fixtures and Appliances in Residential Occupancies

Fixture and Appliance	Maximum Design Flow Rate (gallons per minute)
Bar Sink	1.5
Bathtub	5.5
Bidet	2.0
Clothes Washer[1]	3.5
Combination Bath/Shower	5.5
Dishwasher[1]	1.3
Kitchen Faucet	2.2
Laundry Faucet (with aerator)	2.0
Lavatory Faucet	1.5
Shower, per head	2.0
Water Closet, 1.28 GPF Gravity Tank	3.0

For SI units: 1 gallon per minute = 0.06 L/s

[1] Clothes washers and dishwashers shall have an energy star label.

[6] Estimating Design Flow

There are various ways of estimating peak demand; the historical Hunter's method and other methods considered during this research effort will be discussed.

6.1 Hunter's Method

In 1940, Roy Hunter demonstrated how the binomial probability distribution can describe the incidence of busy water fixtures in a building (Hunter 1940). Given a fixture group of *n* identical fixtures, each with probability *p* of being used, Hunter showed the probability of having exactly *x* fixtures operating simultaneously out of *n* total fixtures has a binomial mass function,

$$b(x; n, p) = \binom{n}{x} (p)^x \, (1-p)^{n-x} \qquad x = 0,1,\dots,n \tag{6.1}$$

Most buildings have a wide assortment of water fixtures. Each fixture group has unique values for *n* and *p* and hence, their distinct version of Equation 6.1. How can the various binomial models be combined to give a single expression for busy fixtures needed to estimate the design flow? Hunter recognized that it was not legitimate to simply add the peak flows from each fixture group. Unfortunately, this problem has no exact solution (Butler, 1993). In a clever move, Hunter introduced *fixture units* to effectively collapse the 99th percentile of the binomial mass function to a single curve of peak flow estimates dependent only on the fixture units. The final result, Hunter's Curve, is the theoretical basis for plumbing codes worldwide (Buchberger *et al.,* 2012; IAPMO, 2015).

The most important input for Hunter's method is total fixture units. A chief drawback of fixture units is that they lack an intuitive physical basis. The fixture unit is a numerical load factor originally measured on a scale of ten. Plumbing fixtures were weighted against the demand curve of the flushometer water closet, which had a value of ten fixture units. This made it possible to reduce the load-producing characteristics of different kinds of fixtures to a common basis. When the load-producing characteristics of plumbing fixtures change, or when extending Hunter's Curve to include new fixtures, finding suitable values for the fixture units while maintaining the weighted scale becomes challenging. Nonetheless, Hunter's fixture unit concept offered an expedient and effective compromise in an era when computations were performed on slide rules, and there was an urgent need to develop uniform standards for premise plumbing.

6.2 Wistort's Method

In 1994, Robert Wistort proposed using the normal approximation for the binomial distribution to estimate peak loads on plumbing systems (Wistort, 1995). Similar to Hunter's approach, the number of busy fixtures *x* is considered to be a random variable with a binomial distribution having a mean E[*x*] = *np* and variance Var[*x*] = *np* (1-*p*). From the normal approximation, the estimate of the 99th percentile of the flow in a building with *K* different fixture groups is

$$Q_{0.99} = \sum_{k=1}^{K} n_k p_k q_k + (z_{0.99})\sqrt{\sum_{k=1}^{K} n_k p_k (1 - p_k) q_k^2} \tag{6.2}$$

In this expression, n_k is the total number of fixtures in fixture type *k*, p_k is the probability that a single fixture in fixture type k is operating, q_k is the flow rate at the busy fixture type *k,* and $z_{0.99}$ is the 99th percentile of the standard normal distribution ($z_{0.99}$ = 2.33). Besides providing a direct analytic estimate of the design flow, the significant advantage of Wistort's direct method is that it avoids the need for fixture unit. In addition, this approach is readily extended to other types of fixtures operating during both congested and non-congested conditions, provided suitable values for *p* and *q* are available.

The binomial distribution applies to the integers and is bounded (0 ≤ *x* ≤ *n*), whereas the normal distribution applies to the real numbers and is unbounded. A poor fit at the tails of the Binomial distribution can lead to inaccuracies when estimating the 99th percentile, the nominal standard for design purposes. The behavior at the tails of a probability distribution is a primary caution with the Wistort method.

In the context of premise plumbing, where *p* values tend to be small, the normal approximation, as defined by the Wistort method in Equation 6.2, works best when the dimensionless term $H(n,p) = \sum n_k \, p_k \geq 5$ (Walpole et al.,1998). This term is called the "Hunter Number" and represents the expected number of simultaneous busy fixtures in the building during the peak period. In the context of residential plumbing, p_k values tend to be small (average $p \approx 0.03$), so the total number of fixtures must be relatively large (e.g., $\Sigma n \geq 150$) to satisfy the condition $H(n,p) \geq 5$. Consequently, Wistort's method will be suitable for estimating demands at buildings with many residential units, but it is not appropriate for single-family homes.

6.3 Modified Wistort Method (Zero-Truncated Poisson-Binomial Distribution)

Hunter and Wistort focused mainly on predicting water demand in large buildings with high fixture counts. Hunter assumed that during peak periods in public buildings, fixtures would experience congested use (*i.e.*, a queue has formed to use a water fixture). Under these conditions, it was virtually certain that at least one fixture in the building would be drawing water at any instant during the peak period. This convenient premise effectively pulls the distribution of busy fixtures away from the lower binomial boundary of zero. The Wistort method for estimating peak flow will also work well in such cases.

In single-family homes and other small-scale dwellings with few people and few fixtures, idle fixtures are the norm, even during peak use. In a building with *K* different and independent fixture groups, the probability, P_0, that all fixtures are idle (*i.e.,* zero demand) is,

$$P_0 = \prod_{k=1}^{K} (1 - p_k)^{n_k} \approx \exp[-H(n,p)] \quad [6.3]$$

With the conventional binomial distribution, the high probability of idle fixtures in the single-family home will exert a "downward pull" on the mean number of busy fixtures, leading to a low bias in the estimated peak flow.

Plumbing systems are not designed for "zero flow," so this condition should not influence the size of a plumbing system. To resolve this dilemma, a *Zero-Truncated Poisson Binomial Distribution* (ZTPBD) is introduced to describe the conditional distribution of busy fixtures in any building, including single-family homes. As shown in Figure 13, the ZTPBD (**blue bars**) arises from the parent Binomial distribution (**red bars**) by truncating the probability mass at $x = 0$ and rescaling the remaining blue mass spikes to ensure the conditional ZTPBD sums to one.

The probability distribution of busy fixtures in a group of $n = 50$ fixtures, each with probability $p = 0.020$ of being in use, is shown in Figure 13. The red bars are for the standard binomial distribution. The blue bars are for the ZTPBD. Because premise plumbing operation implies running water, only the blue graph is appropriate for design purposes.

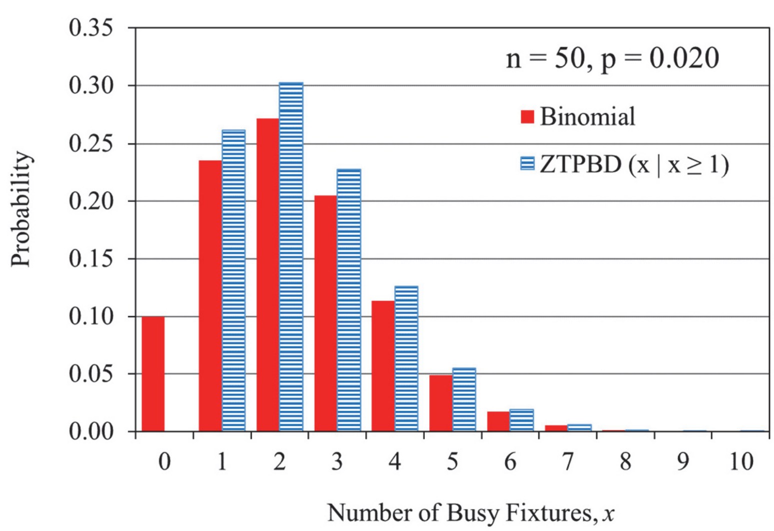


Figure 13: Zero-Truncated Poisson Binomial Distribution (ZTPBD)

The theoretical mean and variance of the ZTPBD are summarized in Table 11. When $np > 5$, $P_0 \to 0$ the **blue** case 2 reduces to **red** case 1, as expected. In practice, this transition typically requires at least 100 fixtures in the building. The results in Table 11 are for one fixture group; most buildings include a variety of fixture groups. The moments shown in Table 11 can be written to account for any arbitrary combination of fixture groups. Hence, the ZTPBD provides the missing link to extend the Wistort method across the full spectrum of applications from large public buildings to small private dwellings. For this reason, the ZTPBD approach is also referred to as the "Modified Wistort Method" (MWM).

Table 11: Mean and Variance of Busy Fixtures in a Building with *n* Identical Fixtures, with a Probability *p* of Being in Use

Case	Probability Model	Mean	Variance	Comment
Red 1	Binomial Distribution	np	$np(1-p)$	Suitable for sizing premise plumbing in large buildings where stagnation during peak periods is unlikely.
Blue 2	Zero-Truncated Poisson - Binomial Distribution	$\frac{np}{1-P_0}$	$\frac{np(1-p)}{1-P_0} - P_0\left(\frac{np}{1-P_0}\right)^2$	Suitable for sizing premise plumbing in any building, including single-family homes, where stagnation during peak periods is likely.

Note: $P_0 = (1 - p)^n$ is the probability of stagnation; P_0 is the mass spike above $X = 0$ in the **red** bars in Figure 13.

Assuming that a normal approximation can be used to describe the upper tail of the ZTPBD, the modified Wistort method for multiple fixture groups in a single building is,

$$Q_{0.99} = \frac{1}{1-P_0}\left[\sum_{k=1}^{K} n_k p_k q_k + (z_{0.99})\sqrt{\left[(1-P_0)\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2\right] - P_0\left(\sum_{k=1}^{K} n_k p_k q_k\right)^2}\right] \quad [6.4]$$

When $H(n,p) > 5$ and $P_0 = 0$, Equation 6.4 reduces to Equation 6.2. In practice, the transition from Equation 6.4 to 6.2 typically requires at least 100-150 fixtures in the building. A nice feature of MWM is that when $n = 1$ and $k = 1$ (the last fixture on the water supply line in the building), Equation 6.4 simplifies $Q_{0.99} = q$, the design flow is simply the nominal demand of the final fixture.

The mathematical proof of Equation 6.4 can be found in Omaghomi (2019), who investigated the properties of a truncated distribution using examples from Exhaustive Enumeration (Section 6.5) and ZTPBD (MWM) using Monte Carlo simulations to validate the output from these models.

6.4 Adjusted Modified Wistort's Method

The frequency factor *z* for the normal approximation can be adjusted to a desired percentile. Wistort (1995) suggested increasing the frequency factor *z* from 2.33 to 2.50 to compensate for the tendency for the normal approximation to under compute at the distribution's tail ends, especially in small systems with a small probability of use. Following that logic, an adjustable frequency factor is introduced in Equation 6.5,

$$Q_a = \frac{1}{1-P_0}\left[\sum_{k=1}^{K} n_k p_k q_k + (A_a)\sqrt{\left[(1-P_0)\sum_{k=1}^{K} n_k p_k (1-p_k) q_k^2\right] - P_0\left(\sum_{k=1}^{K} n_k p_k q_k\right)^2}\right] \quad [6.5]$$

where $A_\alpha = z_\alpha (1 + P_0)$ acts as a modified frequency factor. To illustrate, consider three toilets with a *p*-value of 0.01 and a *z*-score of 2.33 for the 99th percentile. For P_0, Equation 6.3 is used. Therefore, the adjusted *z* score will be computed as,

$$A_{0.99} = 2.33\left(1 + \prod_{k=1}^{K}(1 - 0.01)^3\right) \quad [6.6]$$

Since there is only one kind of fixture (i.e., $K = 1$), $A_{0.99} = 2.33(1 + (1 - 0.01)^3)$ and yielding an adjusted *z* score of 4.58. As $P_0 \rightarrow 0$, the adjusted frequency factor reduces to z_α, and Equation 6.5 simplifies to Equation 6.2.

6.5 Exhaustive Enumeration (Ex.En.) Method

Hunter and Wistort focused on the 99th percentile of the demand expected during the peak period in a building. With today's computational tools, it is possible to numerically generate the entire probability distribution of the water demands at any point and any time in a building. "Exhaustive Enumeration" involves identifying and ranking all possible demand events for a given premise plumbing configuration. To illustrate, consider the peak period in a kitchen/laundry space having a total of $n = 4$ independently operated fixtures listed in Table 12.

Table 12: Parameters Required to Estimate Peak Demand

Fixture	Symbol	n_k	p_k	q_k (gpm)	Rank
Clothes washer	CW	1	0.055	3.5	1
Dishwasher	DW	1	0.005	1.3	4
Kitchen faucet	KF	1	0.020	2.2	2
Laundry faucet	LF	1	0.020	2.0	3

The Hunter Number for the four fixtures in Table 12 is $H(n,p) = \sum n_k\, p_k = 0.10$. Equation 6.3 gives the corresponding probability of zero demand as $P_0 = \exp[-0.10] = 0.904$. There are $2^4 = 16$ mutually exclusive combinations of fixture use, as summarized in Table 13. Column 11 of case 1 gives the probability of zero demand as 0.903, in agreement with the result from Equation 6.3. The estimated 99th percentile of the conditional busy-time demand is $Q_{0.99} = 5.7$ gpm, highlighted in columns [12] and [14] of Table 13.

When the probability of zero demand is high, there can be significant differences in the cumulative probability of the household demands depending on whether an unconditional "total time" or a conditional "busy time" view is adopted. This is illustrated in Figure 14, which shows the probability distribution of total-time demands in blue and busy-time demands in red for the four-fixture example given in Tables 12 and 13. The 90 percent spike at zero demand dominates the blue total-time plot. The median (50th percentile) demand is $Q_{0.50} = 0$ gpm, and the 99th percentile demand is $Q_{0.99} = 3.5$ gpm. In contrast, the red busy-time plot excludes zero demand. The busy-time plot has a median demand of 3.5 gpm and a 99th percentile demand of $Q_{0.99} = 5.7$ gpm, as confirmed in Columns [12] and [14] of Table 13.

While simple in principle, exhaustive enumeration may not always be practical. Due to combinatorial explosion, the size of the problem grows exponentially. The small example in Table 12 with four independent fixtures generated $2^4 = 16$ possible demand outcomes. A typical single-family home with 12 independent fixtures will generate $2^{12} = 4{,}096$ demand outcomes. So, while enumeration is helpful to visualize the jagged probability distribution of discrete fixture demands, it may be restricted to scenarios where the total fixture count *n* is relatively small. Additional examples featuring exhaustive enumeration can be found in Buchberger *et al.* (2012) and Omaghomi and Buchberger (2014).

Table 13: Exhaustive Enumeration of 4 Fixtures with 16 Mutually Exclusive Demand Outcomes

[1]	[2]	[3]	[4]	[5]	[6]	[7]	[8]	[9]	[10]	[11]	[12]	[13]	[14]
Case	**CW**	**DW**	**KF**	**LF**	**P_{CW}**	**P_{DW}**	**P_{KF}**	**P_{LF}**	**Q (gpm)**	**T.T. Probability**	**Q Ranked**	**B.T. Probability**	**B.T. CDF**
1	○	○	○	○	0.945	0.995	0.980	0.980	0.0	0.9030401	0.0	[redacted]	0.0000
2	●	○	○	○	0.055	0.995	0.980	0.980	3.5	0.0525579	1.3	0.046802	0.0468
3	○	●	○	○	0.945	0.005	0.980	0.980	1.3	0.0045379	2.0	0.190072	0.2369
4	○	○	●	○	0.945	0.995	0.020	0.980	2.2	0.0184294	2.2	0.190072	0.4269
5	○	○	○	●	0.945	0.995	0.980	0.020	2.0	0.0184294	3.3	0.000955	0.4279
6	●	●	○	○	0.055	0.005	0.980	0.980	4.8	0.0002641	3.5	0.542058	0.9700
7	●	○	●	○	0.055	0.995	0.020	0.980	5.7	0.0010726	3.5	0.000955	0.9709
8	●	○	○	●	0.055	0.995	0.980	0.020	5.5	0.0010726	4.2	0.003879	0.9748
9	○	●	●	○	0.945	0.005	0.020	0.980	3.5	0.0000926	4.8	0.002724	0.9775
10	○	●	○	●	0.945	0.005	0.980	0.020	3.3	0.0000926	5.5	0.011062	0.9886
11	○	○	●	●	0.945	0.995	0.020	0.020	4.2	0.0003761	5.5	0.000019	0.9886
12	●	●	●	○	0.055	0.005	0.020	0.980	7.0	0.0000054	**5.7**	0.011062	**0.9997**
13	●	●	○	●	0.055	0.005	0.980	0.020	6.8	0.0000054	6.8	0.000056	0.9997
14	●	○	●	●	0.055	0.995	0.020	0.020	7.7	0.0000219	7.0	0.000056	0.9998
15	○	●	●	●	0.945	0.005	0.020	0.020	5.5	0.0000019	7.7	0.000226	1.0000
16	●	●	●	●	0.055	0.005	0.020	0.020	9.0	0.0000001	9.0	0.000001	1.0000
									Sum	1.0		1.0	

Key for Table 13

Column [1]	16 mutually exclusive collectively exhaustive demand outcomes from 4 fixtures
Cols [2] - [5]	● indicates fixture is busy; ○ indicates fixture is idle
Cols [6] - [9]	Shaded values are Prob [fixture is busy]; unshaded values are Prob [fixture is idle]
Column [10]	Demand (gpm) for each outcome, ranging from 0 to 9 gpm. For example, Case 7 represents the simultaneous use of the clothes washer and the kitchen faucet. The total demand is the sum of both draws, 3.5 gpm + 2.2 gpm = 5.7 gpm.
Column [11]	"Total-time" probability of an outcome, found as the product of Cols [6] thru [9]; The zero-demand condition of Case 1 dominates the total-time picture.
Column [12]	Demands of Col [10] ranked from minimum to maximum.
Column [13]	"Busy-Time" conditional probability, found as Col [11] / [1-P_0], for the corresponding ranked demand in Col [12]; Zero demand condition is excluded from busy-time.
Column [14]	Cumulative busy-time conditional probability, from running sum of Col [13]; The 99th percentile is reached at Cases 11 and 12 with a demand of $Q_{0.99}$ = 5.7 gpm.

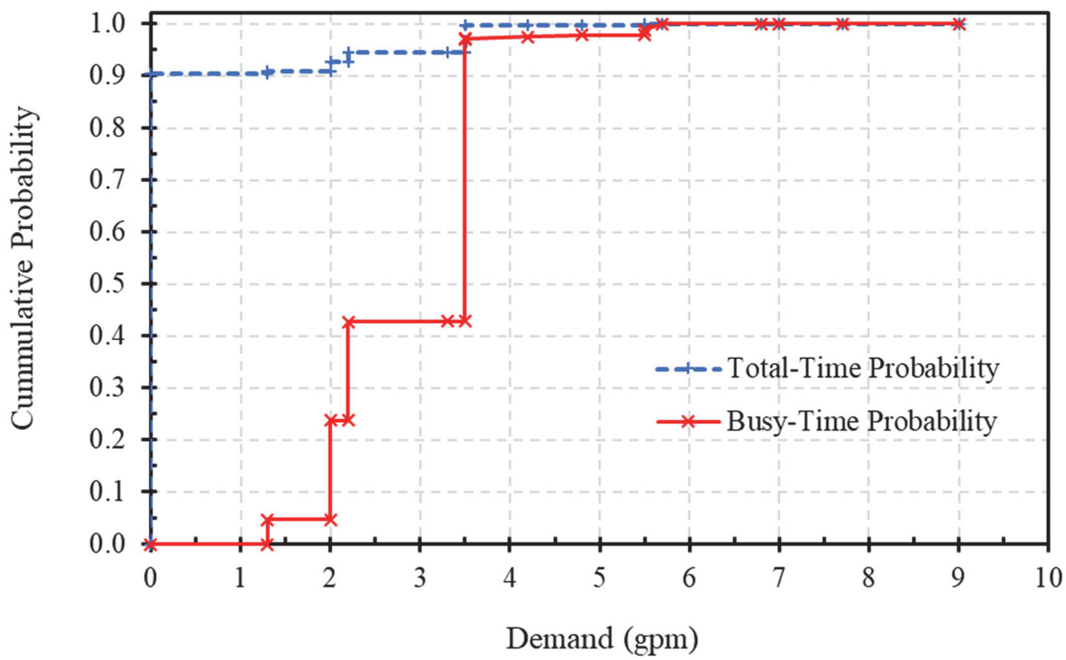


Figure 14: Cumulative Probability Plots for the 4-Fixture Example in Table 13

6.6 Convolution Method

Similar to the Ex.En. method described in Section 6.5, the convolution method identifies and ranks the possible combinations of busy fixtures. Unlike Ex.En., which identifies all the individual busy fixtures, even when there are multiple fixtures in the same group, in the convolution method, the busy fixtures are identified within each group before combining with another group. Herbert (2020) explains the convolution process for two discrete random distributions.

Let X and Y be discrete independent random variables, *i.e.,* K = 2 fixture groups.

Let Z = X + Y. That is, Y = Z – X.

First, calculate the probability density function for the p values and sum the flow rates for the q values for combinations of fixtures within a fixture group using the expressions

$$P[x;\ n, p] = \binom{n}{x} p^x (1-p)^{n-x} \qquad [6.7]$$

$$Q[x;\ n, p] = xq \qquad [6.8]$$

Apply Equations 6.7 and 6.8 to random variable Y, then calculate the p and q values for the convolution of Z using the expressions

$$P(Z = z) = \sum_{x \epsilon X} P_Y(z - x) P_X(x) \qquad [6.9]$$

$$Q(Z = z) = Q_Y(z - x) + Q_X(x) \qquad [6.10]$$

If there are more than two fixture groups (i.e., $K > 2$), calculate the probability density function using Equation 6.7 and their corresponding flow rate with Equation 6.8. Then, the convoluted distribution Z was combined using Equations 6.9 and 6.10. This process is repeated for all K-1 times to obtain the combined probability distribution of all K fixture groups.

Table 14 is a detailed example of the convolution process for two fixture groups, laundry faucet, and clothes washer, shown in Columns [2] through [5] (with parameters in Table 12). Columns [6] and [7] are calculated from Equation 6.7, and column [8] from Equation 6.10. Like Exhaustive Enumeration, the flows are ranked in Column [10], and the “busy time” probability of use is calculated in Column [11]. The estimated 99th percentile of the conditional busy-time demand is $Q_{0.99}$ = 5.5 gpm, highlighted in columns [10] and [12].

Table 14: Convolution of 4 Fixtures (2 Fixture Groups) with 8 Demand Outcomes

<table>
<tr><th>[1]</th><th>[2]</th><th>[3]</th><th>[4]</th><th>[5]</th><th>[6]</th><th>[7]</th><th>[8]</th><th>[9]</th><th>[10]</th><th>[11]</th><th>[12]</th></tr>
<tr><th>Case</th><th>LF</th><th>LF</th><th>LF</th><th>CW</th><th>P_{LF}</th><th>P_{CW}</th><th>Q (gpm)</th><th>T.T. Probability</th><th>Q Ranked</th><th>B.T. Probability</th><th>B.T. CDF</th></tr>
<tr><td>1</td><td>○</td><td>○</td><td>○</td><td>○</td><td>0.94119</td><td>0.945</td><td>0.0</td><td>0.8894264</td><td>0.0</td><td></td><td>0.0000</td></tr>
<tr><td>2</td><td>○</td><td>○</td><td>○</td><td>●</td><td>0.94119</td><td>0.055</td><td>3.5</td><td>0.0517656</td><td>2.0</td><td>0.492475</td><td>0.4925</td></tr>
<tr><td rowspan="3">3</td><td>●</td><td>○</td><td>○</td><td rowspan="3">○</td><td rowspan="3">0.05762</td><td rowspan="3">0.945</td><td rowspan="3">2.0</td><td rowspan="3">0.0544547</td><td rowspan="3">3.5</td><td rowspan="3">0.468155</td><td rowspan="3">0.9606</td></tr>
<tr><td>○</td><td>●</td><td>○</td></tr>
<tr><td>○</td><td>○</td><td>●</td></tr>
<tr><td rowspan="3">4</td><td>●</td><td>○</td><td>○</td><td rowspan="3">●</td><td rowspan="3">0.05762</td><td rowspan="3">0.055</td><td rowspan="3">5.5</td><td rowspan="3">0.0031693</td><td rowspan="3">4.0</td><td rowspan="3">0.010051</td><td rowspan="3">0.9707</td></tr>
<tr><td>○</td><td>●</td><td>○</td></tr>
<tr><td>○</td><td>○</td><td>●</td></tr>
<tr><td rowspan="3">5</td><td>●</td><td>●</td><td>○</td><td rowspan="3">○</td><td rowspan="3">0.00118</td><td rowspan="3">0.945</td><td rowspan="3">4.0</td><td rowspan="3">0.0011113</td><td rowspan="3"><u>**5.5**</u></td><td rowspan="3">0.028663</td><td rowspan="3"><u>**0.9993**</u></td></tr>
<tr><td>●</td><td>○</td><td>●</td></tr>
<tr><td>○</td><td>●</td><td>●</td></tr>
<tr><td rowspan="3">6</td><td>●</td><td>●</td><td>○</td><td rowspan="3">●</td><td rowspan="3">0.00118</td><td rowspan="3">0.055</td><td rowspan="3">7.5</td><td rowspan="3">0.0000647</td><td rowspan="3">6.0</td><td rowspan="3">0.000068</td><td rowspan="3">0.9994</td></tr>
<tr><td>●</td><td>○</td><td>●</td></tr>
<tr><td>○</td><td>●</td><td>●</td></tr>
<tr><td>7</td><td>●</td><td>●</td><td>●</td><td>○</td><td>0.00001</td><td>0.945</td><td>6.0</td><td>0.0000076</td><td>7.5</td><td>0.000585</td><td>1.0000</td></tr>
<tr><td>8</td><td>●</td><td>●</td><td>●</td><td>●</td><td>0.00001</td><td>0.055</td><td>9.5</td><td>0.0000004</td><td>9.5</td><td>0.000004</td><td>1.0000</td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Sum</td><td>1.0</td><td></td><td>1.0</td><td></td></tr>
</table>

Figure 15 illustrates the total and busy time cumulative distribution of flows from the four fixtures. There is an 89% probability of zero demand.

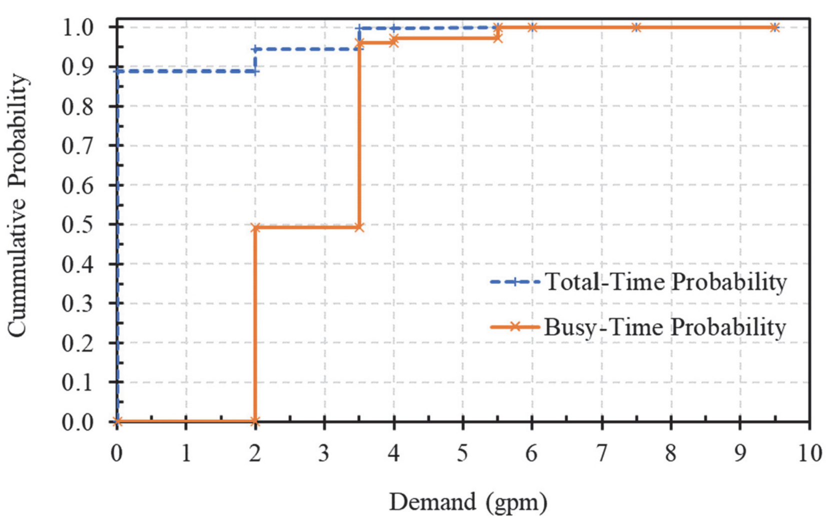


Figure 15: Cumulative Probability Plots for the 4-Fixture Example in Table 14

The examples in Tables 13 and 14 are for four fixtures each. In Table 13, the Ex.En. process has 16 possible demand outcomes, while in Table 14, the convolution process has 8 possible demand outcomes. The convolution process requires $\prod_{k=1}^{K}(n_k + 1)$ outcomes, while Ex.En. has 2^n outcomes. Consequently, given the same number of total fixture counts, the convolution method is more efficient and has the same output as Ex.En. The number of convolution outcomes increases with the number of fixture groups. Note that if all the fixture groups have only one fixture each, the possible demand outcomes in the convolution process will be the same as that from Exhaustive Enumeration.

6.7 $q_1 + q_3$ Method

While applying the exhaustive enumeration approach, it was observed that certain combinations of fixtures consistently tended to strike near the 99th percentile design demand, especially along branch lines at the household level. This led to the "$q_1 + q_3$" method, which works as follows: using recommended fixture demand values in Table 10, rank all fixtures along a branch line in descending order. For instance, the fixture with the largest demand receives the rank of 1 (q_1), the fixture with the second largest demand gets the rank of 2 (q_2), and so on, until all fixtures on a designated branch are ranked. The $q_1 + q_3$ method simply adds the demands for rank 1 and the rank 3 fixtures to obtain an expedient and reasonably good estimate of the 99th percentile demand, often identical to the value generated by a complete exhaustive enumeration.

To demonstrate, consider the four fixtures in Table 12. Rank 1 goes to the clothes washer with its demand of q_1 = 3.5 gpm; Rank 2 goes to the kitchen faucet with its demand of q_2 = 2.2 gpm; Rank 3 goes to the laundry faucet with its demand of q_3 = 2.0 gpm; and Rank 4 goes to the dishwasher with its demand of q_4 =1.3 gpm. According to the $q_1 + q_3$ method, the design demand is 3.5 gpm + 2.0 gpm = 5.5 gpm, produced by the simultaneous use of the clothes washer and the laundry faucet. Excellent results with the $q_1 + q_3$ method have been obtained for *n* approaching 10 or 15 fixtures, provided the overall average *p*-value is not too high.

If a branch line has two or more identical fixtures, each fixture receives a unique rank. Suppose, for example, a second clothes washer was added to Table 12, and the other fixtures remain in place. Rank 1 would stay with clothes washer #1, Rank 2 would now go to clothes washer #2, and Rank 3 would go to the kitchen faucet. The design demand from the $q_1 + q_3$ method now increases slightly to 3.5 gpm + 2.2 gpm = 5.7 gpm, ostensibly produced by the simultaneous use of the clothes washer and the kitchen faucet. If a branch has n = 2 fixtures, then q_3 = 0, and the design demand is q_1, the greater the two fixture demands. Finally, if a branch supplies only one fixture, the design demand is q_1.

All the methods discussed in Section 6 were reviewed for their ease of applicability and suitability to estimate peak demand. The methods selected to update Hunter's curve are discussed in the next section.

[7] Developing the Water Demand Calculator®

Various methods for estimating peak demands in buildings were examined, developed, and tested. Unlike Hunter's 1940 curve, there is no single best computational method to estimate peak demand for all building types and sizes, thus requiring a change in solution strategy with the spatial scale of the plumbing system. On a large scale [i.e., total fixture count, $n > 200$], individual fixtures do not appreciably affect the performance of the water supply system. Consequently, solutions like the Wistort method using well-established continuous probability distributions can be applied readily to estimate demands. Individual fixtures significantly impact system behavior on a small scale [$n < 20$]. At this level, solutions like convolution, exhaustive enumeration, or $q_1 + q_3$ were needed as they account for discrete fixtures in premise plumbing.

The various methods to estimate peak demand in a building explored in this report can be cumbersome even when the designer knows the required parameters *n*, *p,* and *q* for each fixture group. Therefore, to encourage proper use and promote uniform application of these proposed new approaches for estimating peak indoor demands, the Water Demand Calculator® (WDC) was developed. The WDC is a downloadable macro-enabled Microsoft Office Excel spreadsheet that selects the appropriate method of estimating peak demand depending on the user's input. Previously released versions of the WDC (*i.e.,* versions 1.0 through 2.1) had all or some of the $q_1 + q_3$, Ex.En., MWM, and Wistort methods, while the current version WDC 2.2 utilizes the Convolution, Adjusted MWM, and the Wistort method.

Depending on the user's input, *i.e.,* choice of building type and number of fixtures, the fixture probability of use changes as described in Section 4.4. Also, the *Hunter number* ($\Sigma\ np$) is calculated, and the method selected by the WDC can either be in zones A, B, or C, as shown in Figure 16. The peak demand output from zone A (shaded green) is from the Convolution method, while zones B (shaded yellow) and C (shaded red) are Adjusted MWM and Wistort method, respectively. Note that the limitations of Microsoft Office Excel's computing power are not presented in Figure 16. Therefore, some calculations that ought to be in zone A might present results from zone B because of the anticipated long processing times. This ensures optimal user experience and avoids prolonged computing steps. As the number of fixtures increases, the Hunter number also increases and moves into a different region with another method for estimating peak demand depending on the size of the building.

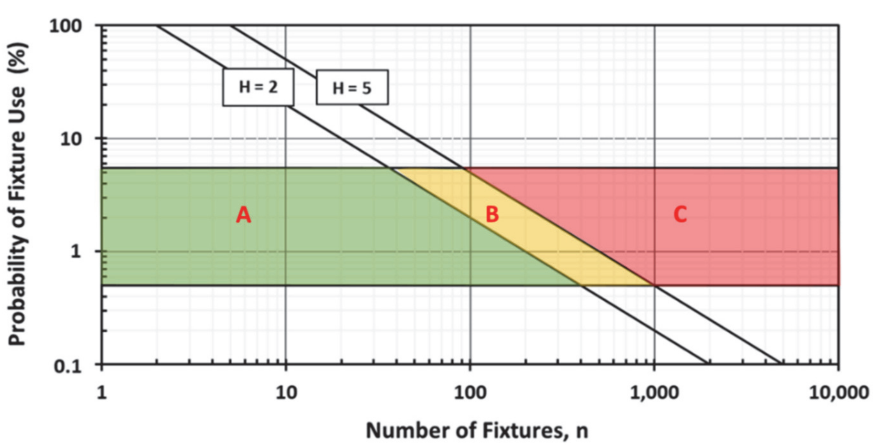
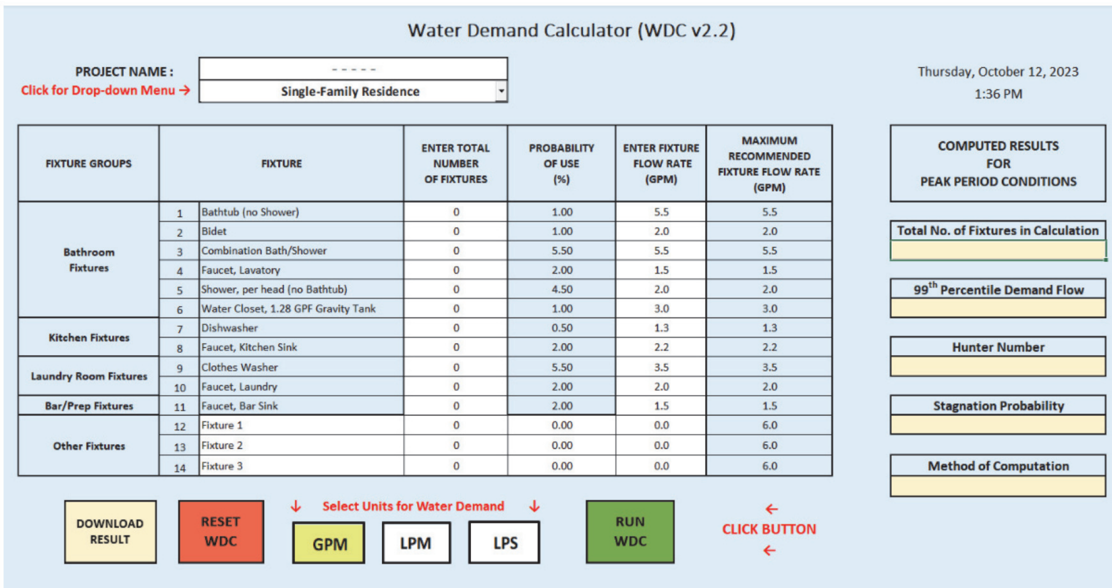


Figure 16: Transition Between the Zones (A = Convolution, B = Adjusted MWM, and C = Wistort method) to Select a Computation Method in the WDC

A screenshot of the input/output template for the WDC is shown in Figure 17. The WDC has white-shaded cells and blue-shaded cells. The fixture probability and flow rate values derived from a national survey of indoor water use at homes with efficient fixtures are in the blue-shaded cells. These values cannot be changed. The white-shaded cells accept input from the user. For instance, the project name, select type of building from a drop-down list, fixture count, and the fixture flow rates are inputs for the user. The flow rates suggested may be reduced where there is allowance in the fixture specifications. The maximum recommended fixture flow rates establish the upper limits for the flow rates the user enters. Clicking the **Run WDC** button will execute the macros and populate the results section of the template. Section 8 discusses estimating peak demand using the WDC for single- and multi-family buildings.



Water Demand Calculator (WDC v2.2)

PROJECT NAME : - - - - -

Click for Drop-down Menu → Single-Family Residence

Thursday, October 12, 2023
1:36 PM

FIXTURE GROUPS		FIXTURE	ENTER TOTAL NUMBER OF FIXTURES	PROBABILITY OF USE (%)	ENTER FIXTURE FLOW RATE (GPM)	MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
Bathroom Fixtures	1	Bathtub (no Shower)	0	1.00	5.5	5.5
	2	Bidet	0	1.00	2.0	2.0
	3	Combination Bath/Shower	0	5.50	5.5	5.5
	4	Faucet, Lavatory	0	2.00	1.5	1.5
	5	Shower, per head (no Bathtub)	0	4.50	2.0	2.0
	6	Water Closet, 1.28 GPF Gravity Tank	0	1.00	3.0	3.0
Kitchen Fixtures	7	Dishwasher	0	0.50	1.3	1.3
	8	Faucet, Kitchen Sink	0	2.00	2.2	2.2
Laundry Room Fixtures	9	Clothes Washer	0	5.50	3.5	3.5
	10	Faucet, Laundry	0	2.00	2.0	2.0
Bar/Prep Fixtures	11	Faucet, Bar Sink	0	2.00	1.5	1.5
Other Fixtures	12	Fixture 1	0	0.00	0.0	6.0
	13	Fixture 2	0	0.00	0.0	6.0
	14	Fixture 3	0	0.00	0.0	6.0

COMPUTED RESULTS FOR PEAK PERIOD CONDITIONS

Total No. of Fixtures in Calculation

99th Percentile Demand Flow

Hunter Number

Stagnation Probability

Method of Computation

DOWNLOAD RESULT

RESET WDC

↓ Select Units for Water Demand ↓

GPM

LPM

LPS

RUN WDC

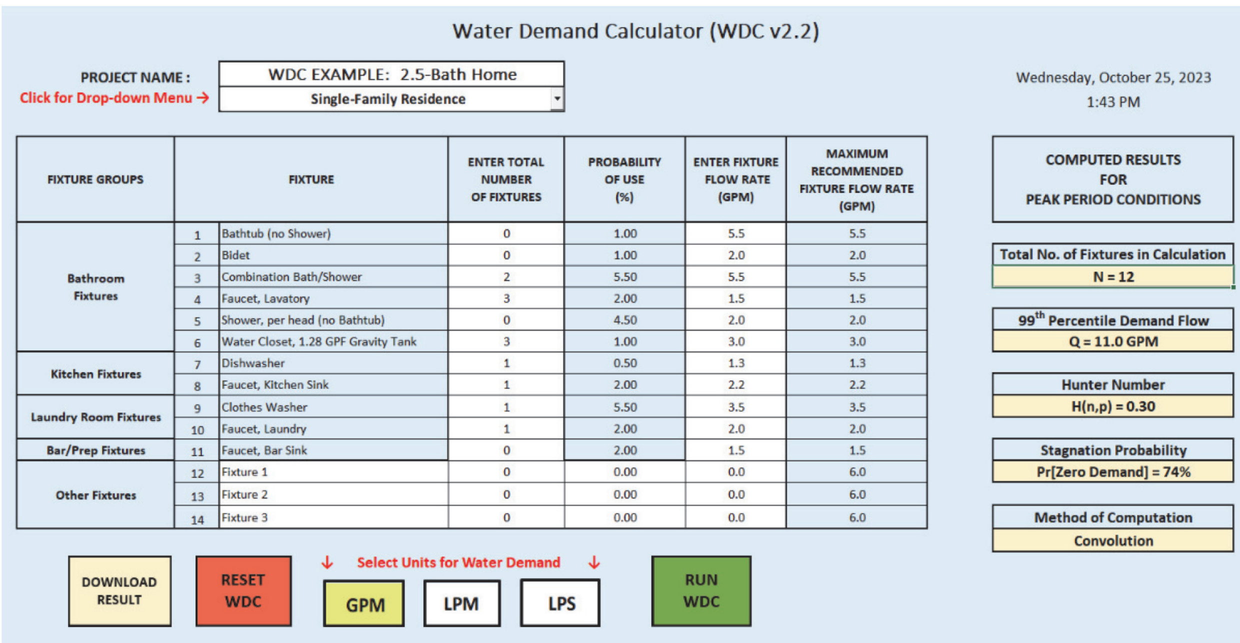
← CLICK BUTTON ←

Figure 17: Screenshot of the Input/Output Template for the WDC

[8] Estimating Peak Water Demand in Buildings

8.1 Single-Family Home

To use the WDC for single-family homes, select “Single-Family Residence” in the dropdown list — the default setting, and then input the number of fixtures in the building. Figure 18 shows the fixture count for a 2.5 bath home with 12 fixtures and the peak demand estimate for the point of entry at the water meter as 11.0 gpm. Other results on the right-hand side of the template indicate a 74% probability of stagnation, *i.e.,* zero demand, and the Hunter number is 0.30, *i.e.,* less than one busy fixture on average during the peak period of water use. Convolution was used as the computation method (see zone A in Figure 16).



FIXTURE GROUPS		FIXTURE	ENTER TOTAL NUMBER OF FIXTURES	PROBABILITY OF USE (%)	ENTER FIXTURE FLOW RATE (GPM)	MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
Bathroom Fixtures	1	Bathtub (no Shower)	0	1.00	5.5	5.5
	2	Bidet	0	1.00	2.0	2.0
	3	Combination Bath/Shower	2	5.50	5.5	5.5
	4	Faucet, Lavatory	3	2.00	1.5	1.5
	5	Shower, per head (no Bathtub)	0	4.50	2.0	2.0
	6	Water Closet, 1.28 GPF Gravity Tank	3	1.00	3.0	3.0
Kitchen Fixtures	7	Dishwasher	1	0.50	1.3	1.3
	8	Faucet, Kitchen Sink	1	2.00	2.2	2.2
Laundry Room Fixtures	9	Clothes Washer	1	5.50	3.5	3.5
	10	Faucet, Laundry	1	2.00	2.0	2.0
Bar/Prep Fixtures	11	Faucet, Bar Sink	0	2.00	1.5	1.5
Other Fixtures	12	Fixture 1	0	0.00	0.0	6.0
	13	Fixture 2	0	0.00	0.0	6.0
	14	Fixture 3	0	0.00	0.0	6.0

Figure 18: Example Demand for 2.5 Bath Home

Similarly, to run the calculator for the hot water branch, remove the fixtures without hot water use and run the calculator. Table 15 summarizes the result for a 2.5 bath single family service line and hot water branch.

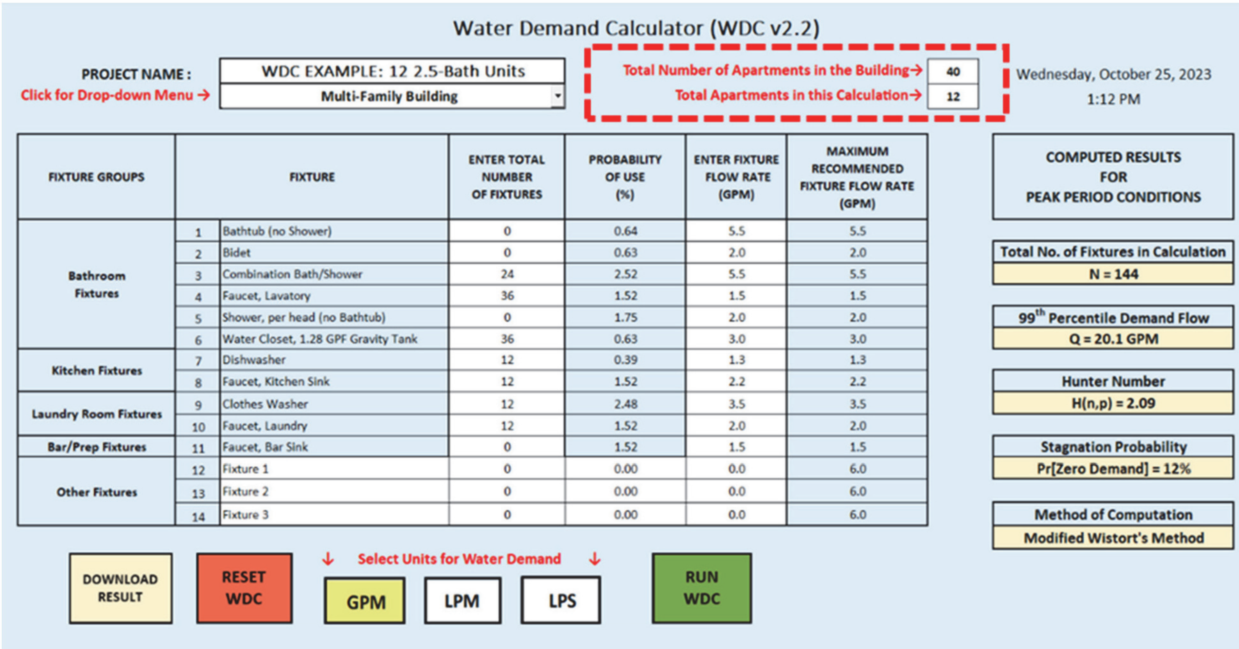
In this hot-water supply example, although the number of fixtures drops from 12 to 9, the expected peak demand remains the same. In contrast to Hunter’s method, which has increased fixture units and demand flow with an increase in fixture count, the Ex.En. (and Convolution) method depends on a combination of all three parameters n, p, and q. An increase in fixture count (with its flow properties p and q) increases the flow diversity; that is, there is an increase in the variety of possible flow rates created from the combinations of busy fixtures. This increase in flow diversity creates a new flow probability distribution that differs from the distribution before adding new fixtures. The new fixture adds to the variety of possible demand flows, changing their probability of occurrence and other flow properties (combined flow mean or variance). Therefore, a similar or sometimes even decreased demand output with an increase in fixture count is possible, especially where there is some probability of stagnation during the peak period of water use (Omaghomi 2019).

Table 15: Example Demand Calculations for Single-Family Unit

Fixture	*p*-value	*q*-value (gpm)	Number of Fixtures, *n*	
			Service Line	Hot Water Branch
Combination Bath/Shower	0.055	5.5	2	2
Faucet, Lavatory	0.020	1.5	3	3
Water Closet	0.010	3.0	3	0
Dishwasher	0.005	1.3	1	1
Faucet, Kitchen Sink	0.020	2.2	1	1
Clothes Washer	0.055	3.5	1	1
Faucet, Laundry	0.020	2.0	1	1
		Total Fixture Count	12	9
		The region in Figure 16	A	A
		Hunter Number, $H(n, p)$	0.3	0.27
		Probability of Zero Demand During Peak Period	74%	76%
		99th Percentile Demand $Q_{0.99}$ (gpm)	11	11

8.2 Multi-Family Building

To use the WDC for a multi-family building, select "Multi-Family Buildings" in the dropdown list and enter the total number of apartments in the building and the total apartment units in the calculation. The total number of apartments entered in the calculation determines the fixture's probability of use. As explained in Section 4.4, the peak period probability of use decreases as the number of apartments increases. Figure 19 shows the WDC input template with an example calculating the water supply for 12 apartments (each with a water heater) in a 40-unit apartment building. Figure 20 shows the WDC input template with an example calculating demand for the service pipe for all 40 apartments in a 40-unit apartment building. The demand for the 12 apartments is computed using the adjusted MWM, while the demand for the 40 apartments is from the Wistort method. Table 16 summarizes the input and output for the water supply to 12 apartments and the service line to all 40 apartments with 2.5 baths.



Water Demand Calculator (WDC v2.2)

PROJECT NAME : WDC EXAMPLE: 12 2.5-Bath Units

Click for Drop-down Menu → Multi-Family Building

Total Number of Apartments in the Building→ 40

Total Apartments in this Calculation→ 12

Wednesday, October 25, 2023

1:12 PM

FIXTURE GROUPS		FIXTURE	ENTER TOTAL NUMBER OF FIXTURES	PROBABILITY OF USE (%)	ENTER FIXTURE FLOW RATE (GPM)	MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
Bathroom Fixtures	1	Bathtub (no Shower)	0	0.64	5.5	5.5
	2	Bidet	0	0.63	2.0	2.0
	3	Combination Bath/Shower	24	2.52	5.5	5.5
	4	Faucet, Lavatory	36	1.52	1.5	1.5
	5	Shower, per head (no Bathtub)	0	1.75	2.0	2.0
	6	Water Closet, 1.28 GPF Gravity Tank	36	0.63	3.0	3.0
Kitchen Fixtures	7	Dishwasher	12	0.39	1.3	1.3
	8	Faucet, Kitchen Sink	12	1.52	2.2	2.2
Laundry Room Fixtures	9	Clothes Washer	12	2.48	3.5	3.5
	10	Faucet, Laundry	12	1.52	2.0	2.0
Bar/Prep Fixtures	11	Faucet, Bar Sink	0	1.52	1.5	1.5
Other Fixtures	12	Fixture 1	0	0.00	0.0	6.0
	13	Fixture 2	0	0.00	0.0	6.0
	14	Fixture 3	0	0.00	0.0	6.0

COMPUTED RESULTS FOR PEAK PERIOD CONDITIONS

Total No. of Fixtures in Calculation: N = 144

99th Percentile Demand Flow: Q = 20.1 GPM

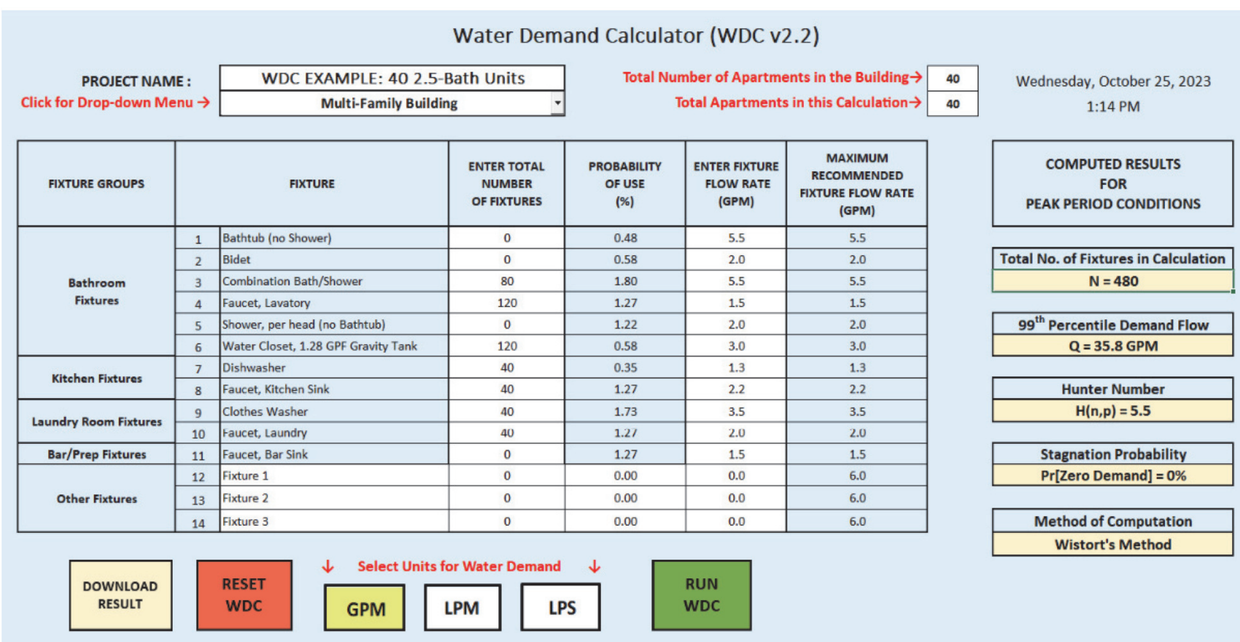
Hunter Number: H(n,p) = 2.09

Stagnation Probability: Pr[Zero Demand] = 12%

Method of Computation: Modified Wistort's Method

DOWNLOAD RESULT | RESET WDC | ↓ Select Units for Water Demand ↓ GPM | LPM | LPS | RUN WDC

Figure 19: Example Demand for the Water Supply to 12 Apartments with 2.5 Baths



Water Demand Calculator (WDC v2.2)

PROJECT NAME : WDC EXAMPLE: 40 2.5-Bath Units

Click for Drop-down Menu → Multi-Family Building

Total Number of Apartments in the Building→ 40

Total Apartments in this Calculation→ 40

Wednesday, October 25, 2023

1:14 PM

FIXTURE GROUPS		FIXTURE	ENTER TOTAL NUMBER OF FIXTURES	PROBABILITY OF USE (%)	ENTER FIXTURE FLOW RATE (GPM)	MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
Bathroom Fixtures	1	Bathtub (no Shower)	0	0.48	5.5	5.5
	2	Bidet	0	0.58	2.0	2.0
	3	Combination Bath/Shower	80	1.80	5.5	5.5
	4	Faucet, Lavatory	120	1.27	1.5	1.5
	5	Shower, per head (no Bathtub)	0	1.22	2.0	2.0
	6	Water Closet, 1.28 GPF Gravity Tank	120	0.58	3.0	3.0
Kitchen Fixtures	7	Dishwasher	40	0.35	1.3	1.3
	8	Faucet, Kitchen Sink	40	1.27	2.2	2.2
Laundry Room Fixtures	9	Clothes Washer	40	1.73	3.5	3.5
	10	Faucet, Laundry	40	1.27	2.0	2.0
Bar/Prep Fixtures	11	Faucet, Bar Sink	0	1.27	1.5	1.5
Other Fixtures	12	Fixture 1	0	0.00	0.0	6.0
	13	Fixture 2	0	0.00	0.0	6.0
	14	Fixture 3	0	0.00	0.0	6.0

COMPUTED RESULTS FOR PEAK PERIOD CONDITIONS

Total No. of Fixtures in Calculation: N = 480

99th Percentile Demand Flow: Q = 35.8 GPM

Hunter Number: H(n,p) = 5.5

Stagnation Probability: Pr[Zero Demand] = 0%

Method of Computation: Wistort's Method

DOWNLOAD RESULT | RESET WDC | ↓ Select Units for Water Demand ↓ GPM | LPM | LPS | RUN WDC

Figure 20: Example Demand for the Service Line to 40 Apartments with 2.5 Baths

Table 16: Example Demand Calculations for Multi-Family Buildings

Fixture	*q*-value (gpm)	12 Units		40 Units	
		n	*p*	*n*	*p*
Combination Bath/Shower	5.5	24	0.0252	80	0.018
Faucet, Lavatory	1.5	36	0.0152	120	0.0127
Water Closet	3.0	36	0.0063	120	0.0058
Dishwasher	1.3	12	0.0039	40	0.0035
Faucet, Kitchen Sink	2.2	12	0.0152	40	0.0127
Clothes Washer	3.5	12	0.0248	40	0.0173
Faucet, Laundry	2.0	12	0.0152	40	0.0127
Total Fixture Count		144		480	
The region in Figure 16		B		C	
Hunter Number, H (*n, p*)		2.09		5.5	
Probability of Zero Demand During Peak Period		12%		0%	
99^{th} Percentile Demand $Q_{0.99}$ (gpm)		20.1		35.8	

After using the Water Demand Calculator® to find the estimated demand for each pipe segment of a water distribution system, the pipe size can be found by consulting your plumbing code, and examples can be found in Appendix B.

[9] General Considerations

9.1 Effect on System Size

Plumbing systems sized by current plumbing codes using Hunter's Curve are commonly known to be oversized (USNCCIB 1974, Wistort, 1995). The divergence between code estimated peak flow rates and actual measured peak flow rates becomes even more noticeable as fixture units increase. Material and installation costs are greater than necessary. Pumps do not perform at their scheduled duty points. Energy efficiency drops. Meter-based equipment calibrated for higher flow rates suffers from poor accuracy or no readings. Water softener resin beds can experience channeling, a scenario where the velocity through the tank is too slow and water channels through the resin, resulting in hard water passing through untreated. The solution to these issues is an updated plumbing pipe sizing method.

The WDC resolves these discrepancies by reducing construction and operating costs while increasing energy, material, and performance efficiencies. To validate this sizing system, data has been obtained from several new multi-family buildings with efficient fixtures. Becking *et al.* (2022) confirmed that the monitored flow rates from 20 multi-family buildings monitored between 9 to 823 days did not exceed the predicted flow rates from the WDC. The design estimates from the WDC were between two to six times the observed flow rates. This was expected because conservative fixture *p*-values were selected in the design of the WDC.

The WDC for sizing the water distribution system is currently limited to single and multi-family dwellings; however, it is anticipated that with known fixture parameters, its methods can be expanded to other building types, including healthcare, industrial, and commercial applications. Additional data collection would be required to estimate the correct probabilities and flow rates for fixtures in each building type. There is also the potential for this sizing system to be programmed into Building Information Modeling (BIM) design software used in the construction of buildings. The program would recognize the fixtures connected to a given section of pipe and suggest an appropriate pipe size based on the anticipated peak flow rate.

9.2 Sensitivity Analysis

Three key parameters are needed to apply the modified Wistort method as defined in Equation 6.5: *n, p, q*. The fixture count, *n*, is readily determined from the Mechanical, Electrical and Plumbing (MEP) plans in the construction drawings. Current rendering software commonly used in the Architectural, Engineering, and Construction industry can provide automatic fixture counts. The probability of fixture use, *p*, needs to be provided by monitoring the frequency of fixture use, as discussed in Section 4 and shown in Table 9. So far, the fixture *p*-values from residential data have been below 0.06, making the design values of *p* likely to be in a relatively narrow range for any given fixture. The nominal flow rate, *q*, for efficient fixtures can be obtained from the manufacturer's literature. Additional guidance on fixture flow rates is given in Table 10.

There is bound to be uncertainty surrounding the selection of the appropriate *p* and *q* values. The modified Wistort equation given in Equation 6.5 is much more sensitive to a choice of *q* than a choice of *p*. To illustrate, Figure 21 shows how the computed value of $Q_{0.99}$ varies with changes in *p* (blue dashed lines) and *q* (red solid line). For example, doubling all the fixture flow rates (*q*) will effectively double the value of $Q_{0.99}$. In comparison, doubling all the fixture probability of use values (*p*) will increase the value of $Q_{0.99}$ by 15 – 75%. This increase is magnified slightly when the fixture count also increases.

As noted in Section 5 and Table 10, some of the fixtures in the WDC were not included in the database. The faucet group did not differentiate between the lavatory, kitchen, bar sink, and laundry sink faucet. Since the faucet group in the database has a representative *p*-value of 0.02, all faucet types in the WDC for residential applications were assigned the same *p*-value. A slight variation between the actual frequency of use between different faucet types will not significantly impact the $Q_{0.99}$. The *q*-value does differ between the faucet types and is more significant for the $Q_{0.99}$. Therefore, other fixtures not listed in the WDC (e.g., kitchen pot filler, dog bath) can be assigned an approximate *p*-value, which is less sensitive than changing the *q*-value.

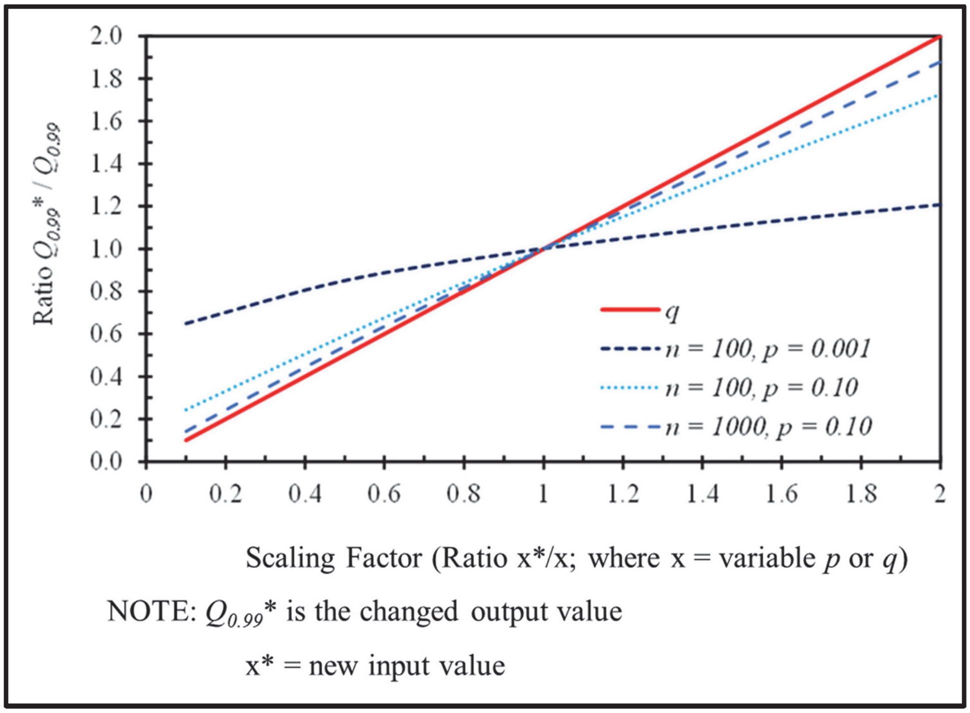


Figure 21: Effect of Changing *p* and *q* on the Value of $Q_{0.99}$ Computed from Equation 6.3

[10] Conclusions and Recommendations

A national database with high-resolution reading logged at 10-second intervals in 1038 single-family residential buildings in 62 cities in 9 states was analyzed to estimate the probability that a fixture is busy during the peak period of water use in a building. Although there was a positive trend in some fixture *p*-values with the number of occupants, there was no statistically significant difference between the fixture *p*-values for the number of occupants. Therefore, the maximum fixture *p*-value from the probability estimates based on the number of occupants in a building was selected as a representative fixture *p*-value. These fixture *p*-values are for indoor water use at residential buildings with efficient fixtures and serve as a baseline for water use at efficient fixtures.

This report also summarizes a simulated exercise extending the fixture *p*-values from single-family to multi-apartment buildings. A simple expression was developed to calculate the fixture *p*-values in multi-apartment buildings. Fixture *p*-values reduce as the number of units increases because the independent units do not necessarily have synchronized peak hours of water use.

The computational methods for estimating water supply demand for single and multi-family dwellings identified in this report and formulated in the Water Demand Calculator® will help mitigate excessive over-design resulting from Hunter's Curve as the current method used in US plumbing codes.

The accuracy of the methods depends upon the key parameters of fixture use probability and fixture flow rate. This report's end-use of water data are from the largest available US residential end-use of water survey (REUWS), representing homes with low water consumption fixtures. Although this trimmed a large portion of available data that did not contain efficient fixtures, the sample size was adequate for statistical analysis. The fixture *p*-values and *q*-values are sound based on the data available. The work described here far exceeds the data used in developing the Hunter method, which consisted of a few hotels and government offices.

The modified Wistort method is a tractable analytical expression to directly estimate the design discharge for a broad spectrum of buildings, ranging from small private dwellings to large public facilities. A key advantage of the Wistort approach is that it does not rely on arbitrary fixture units and is not calibrated to any particular fixture type or a specific building type. It is well suited to predict the demand from busy fixtures in large plumbing systems, especially when the Hunter Number exceeds 5. Both the Wistort and the modified Wistort method are easily programmed on an electronic spreadsheet, can be offered as a convenient "app" to engineers and inspectors, and are readily incorporated into emerging digital tools (i.e., BIM) of the Architectural, Engineering, and Construction industry.

In summary, the probability describes the user's tendency to activate each fixture, and the flow rate is the rate at which each fixture consumes water. The WDC takes the three key parameters, *n, p,* and *q,* to calculate the estimated supply demand for each part of the water distribution system, from a single fixture supply branch to an entire multi-family building.

The WDC was adopted into the 2018 Uniform Plumbing Code. Since its adoption, as summarized below, several studies have highlighted the benefits of using the WDC to estimate peak demand for indoor pipe sizing in residential buildings.

- The WDC has undergone several versions (1.0 through 2.2) to improve its speed, accuracy, and user experience.
- Omaghomi *et al.* (2020) report a remarkable comparison between observed and predicted peak demand using the WDC in 11 multi-family residential buildings with 20 or more units.
- Stantec (2020) reports construction and labor cost savings in sizing three sizes of buildings in three different cities using the WDC compared to Hunter's curve.
- AWE (2021) reports substantial cost savings from service connection and water meter fees due to downsizing from using the right sizing methodologies contained in the WDC.

- Becking *et al.* (2022) report a prediction of peak demand within 2 to 6 times the factor of safety using the WDC for 20 multi-family residential buildings across three states compared to observed peaks.
- Arup (2023) reports water, energy, and carbon emission savings from using the WDC to size indoor pipes in one single-family home and three multi-family building prototypes.
- Jingjuan F. *et al.* (2024) of TRC Companies and Frontier Energy led a Codes and Standards Enhancement initiative and reported water and energy savings from using the WDC to size indoor pipes in 4 multifamily building prototypes.
- Other benefits of right-sizing indoor pipes include improved water and energy efficiency, improved water quality by reducing water age, and the possible reduced risk of *Legionella* growth.

Some specific areas for potential future research include:

- Implement a broad national field program to measure instantaneous peak indoor water demands in the residential sector and other end users (commercial, institutional, *etc*.).
- Analyze data from the national field monitoring program to extend and refine estimates of *p* and *q* for a wide range of end uses (residential, commercial, institutional, public, *etc*).
- Establish a comprehensive "cloud bank" to serve as an online digital repository for *p* and *q* values for every fixture in use today or in the future.

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APPENDICES

A – Exploratory Data Analysis

Figure A1 shows the different decades in which the surveyed homes were built. The 1038 homes analyzed were built as late as the early 1920s. About 95% of the homes with no record of the year they were built fall into a group coded as "EPA new homes" constructed sometime after 2000. Therefore, about 68% of the homes analyzed were erected sometime before 1990. The distribution of trace days of the surveyed homes after eliminating days of zero or minimal water use is shown in Figure A2, with an average of 11 trace days per home. In addition, the distribution of the number of residents in the surveyed homes is in Figure A3, with an average of about three residents per monitored home.

Box and whisker plots showing the statistical distribution of calculated and measured water use details grouped by fixture efficiency are represented by figures A4 – A8. All the fixtures had several outliers for the measured and calculated water use details. Other statistical details on flow rate, volume of water used per capita per day at a fixture, and duration of fixture use are in Table A1.

Figure A4 shows a wide distribution of flow rates for bathtubs, clothes washers, and toilets. The fixture efficiency is inversely proportional to the fixture mean flow rates within each fixture group. Dishwashers and faucets had the lowest flow rate, while bathtubs had the highest flow rates.

Figures A5 and A6 show fixtures with high and low water usage per capita per day. Within each fixture group categorized by efficiency levels, the mean volume of water used per capita per day increased with a decrease in fixture efficiency. All surveyed homes had more than 75% of water use less than 25 gallons per fixture per capita per day.

In Figure A7, the shower efficiency was directly proportional to the average duration of shower use (i.e., Homes with ultra-efficient showers had longer average bath times than homes with inefficient showers). In Figures A7 and A8, other fixtures categorized by their efficiencies had inversely proportional relationship between fixture efficiency and the average duration of fixture use. Only inefficient dishwashers showed a distinct non-overlapping distribution of duration of water use at a fixture compared to other fixtures differentiated by their efficiencies.

Table A2 shows the average fixture count and the sample size distribution for the different categories of fixture efficiencies in homes grouped by their number of residents. The details in Table A2 are the sample distribution for the homes grouped to determine the peak hour probability of fixture use. Statistical details of the peak hour probability of fixture use in the surveyed homes are shown in Table A3. A wide range of peak hour probability values were calculated; however, the low average values result from many homes with zero water use at some fixtures, even during the peak hour of water use.

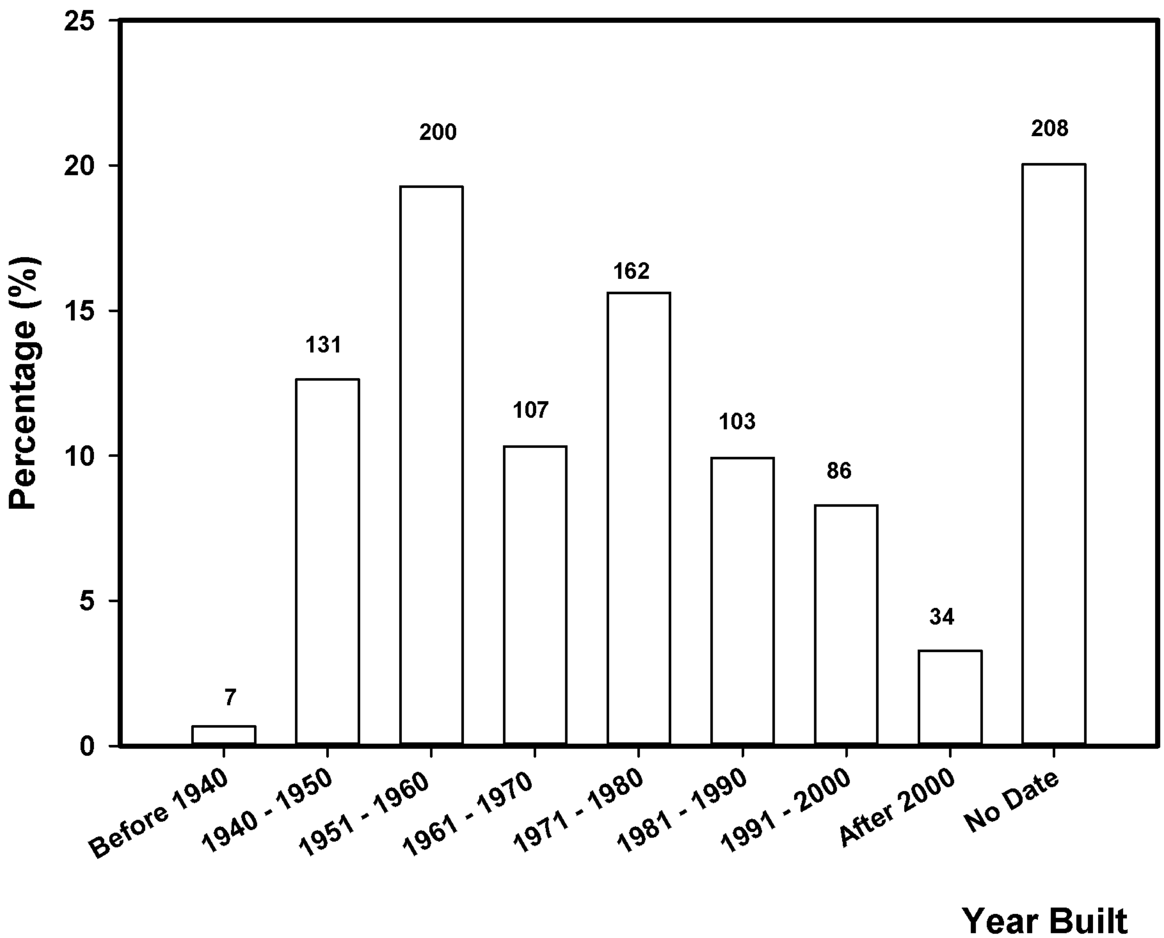


Figure A1: Distribution of Surveyed Homes with Respect to Year Built

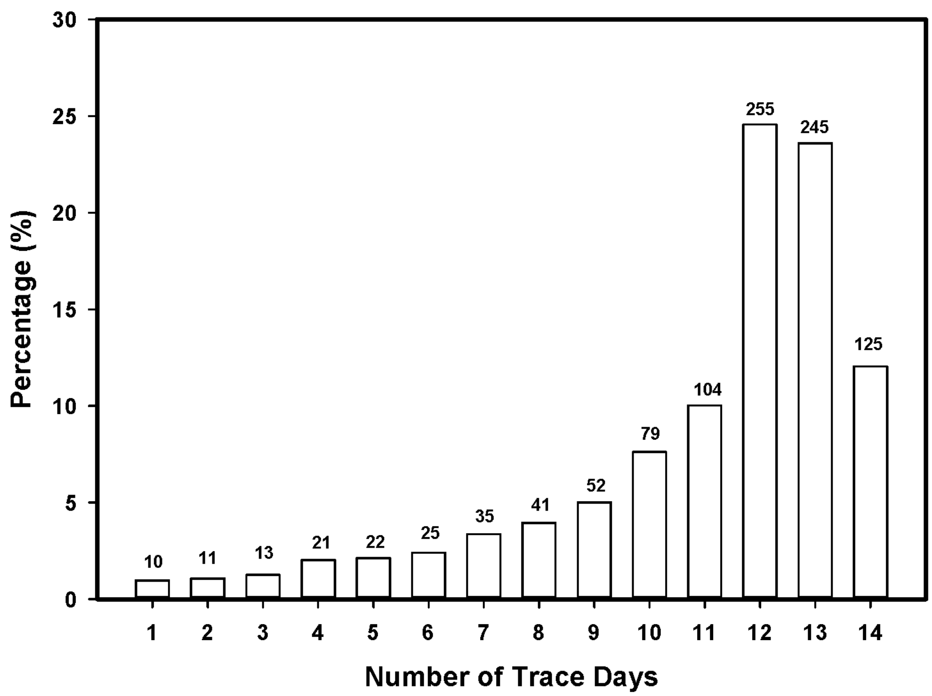


Figure A2: Distribution of Valid Trace Days for 1038 Households (Average of 11 Days Per Household)

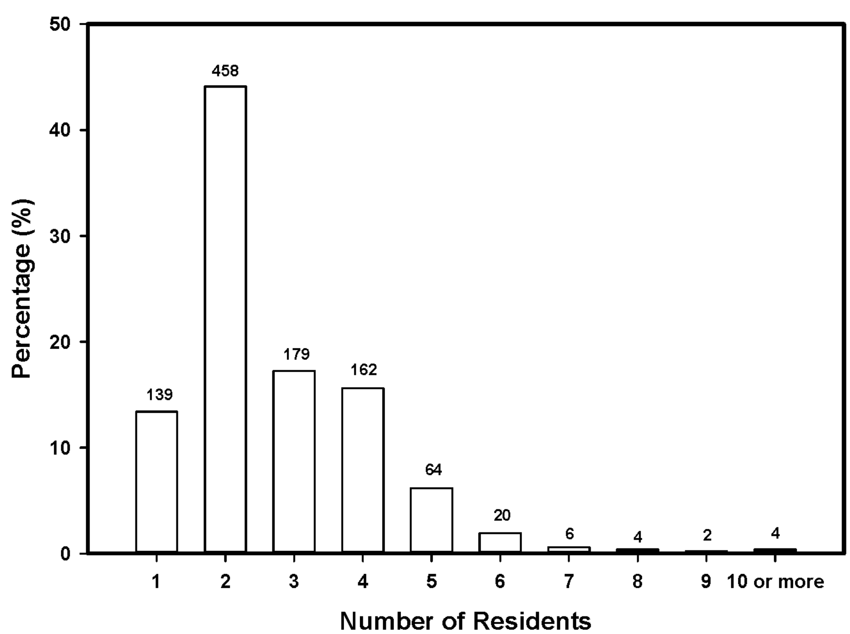


Figure A3: Distribution of Occupancy Level in 1038 Households (Average of 2.72 Residents Per Household)

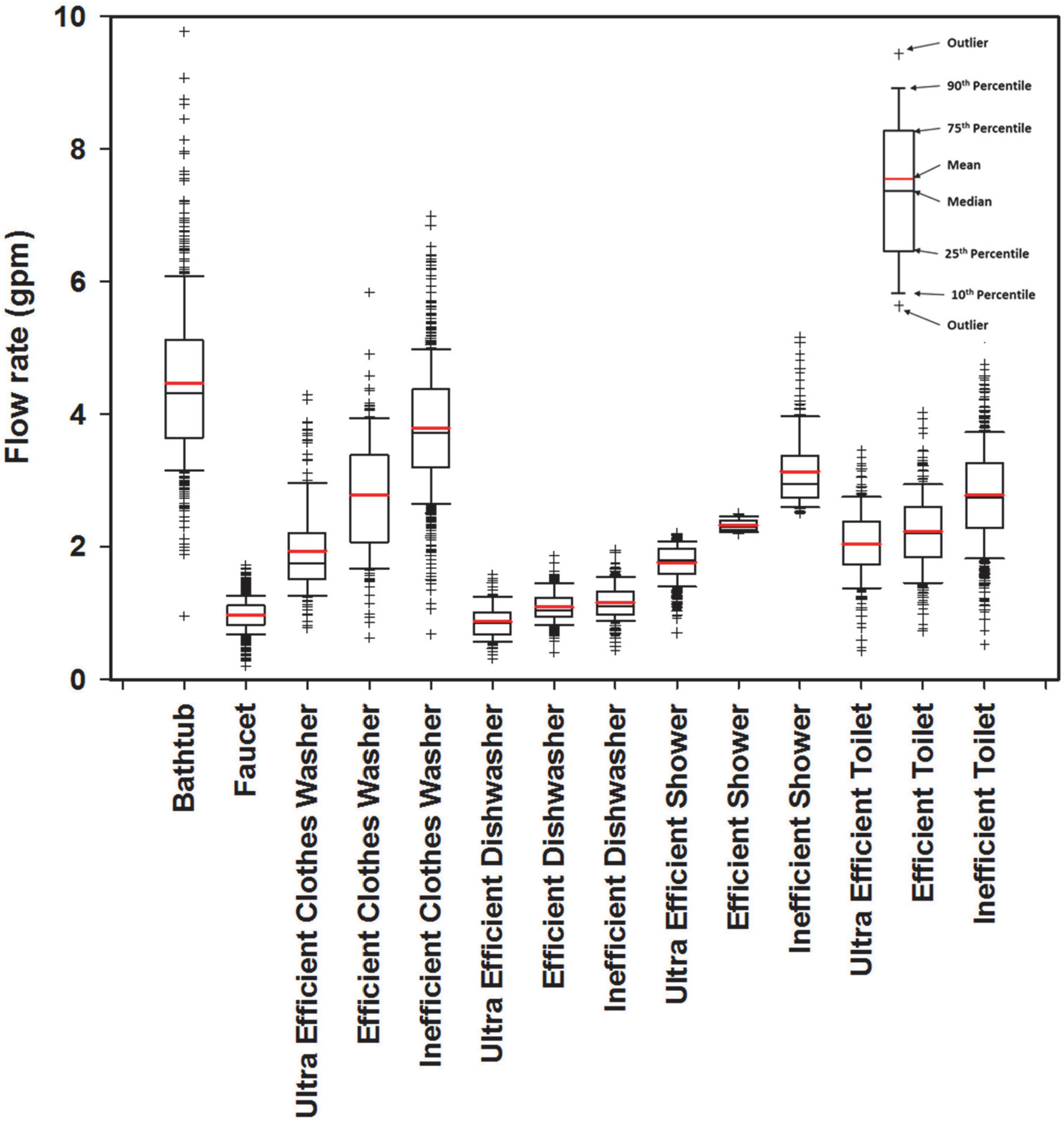


Figure A4: Box and Whisker Plot of Flow Rate for the Different Fixture Efficiency Levels

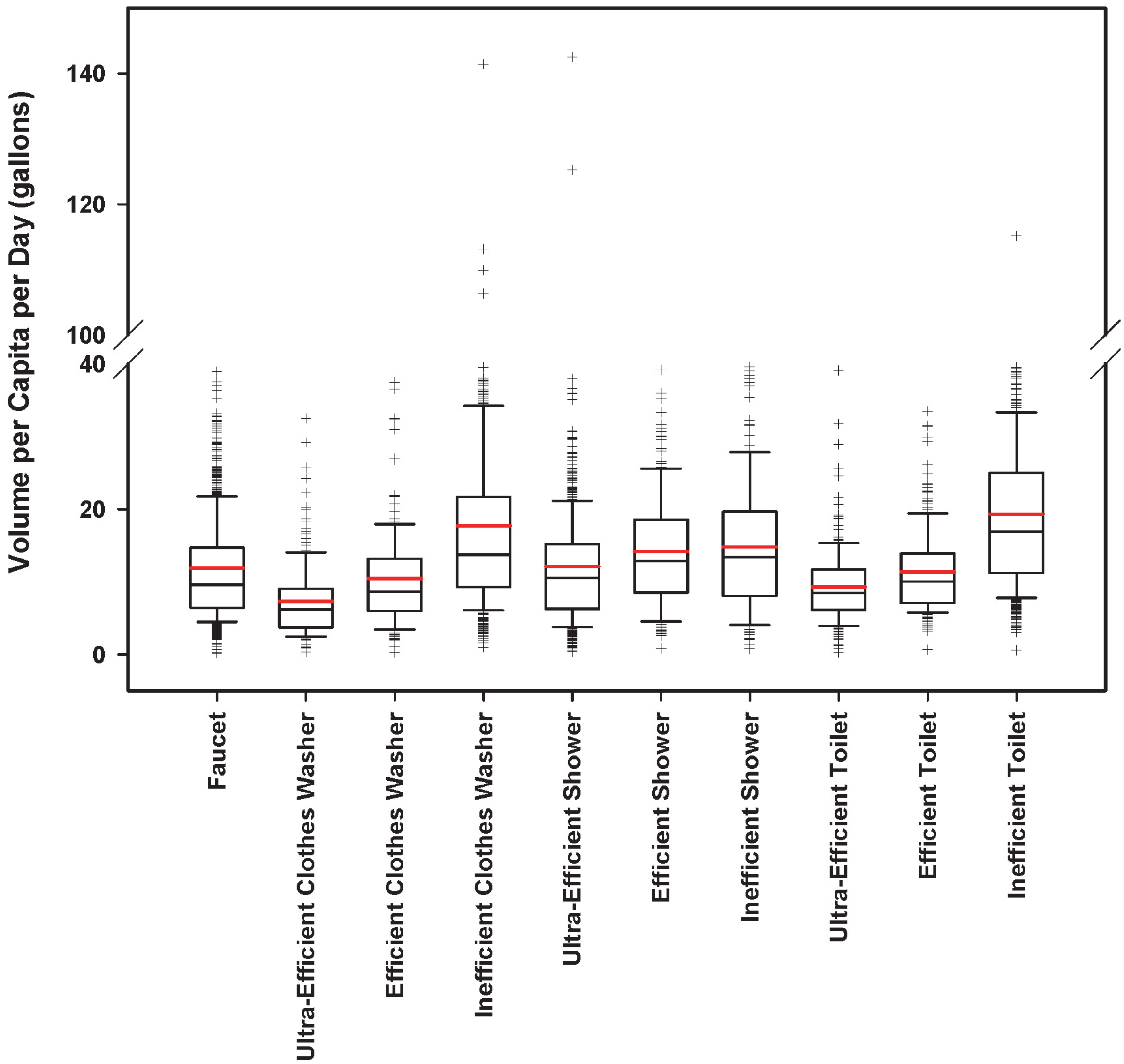


Figure A5: Box and Whisker Plot of Water Usage Per Capita Per Day For Faucets and the Different Efficiency Levels of Clothes Washers, Showers, and Toilets

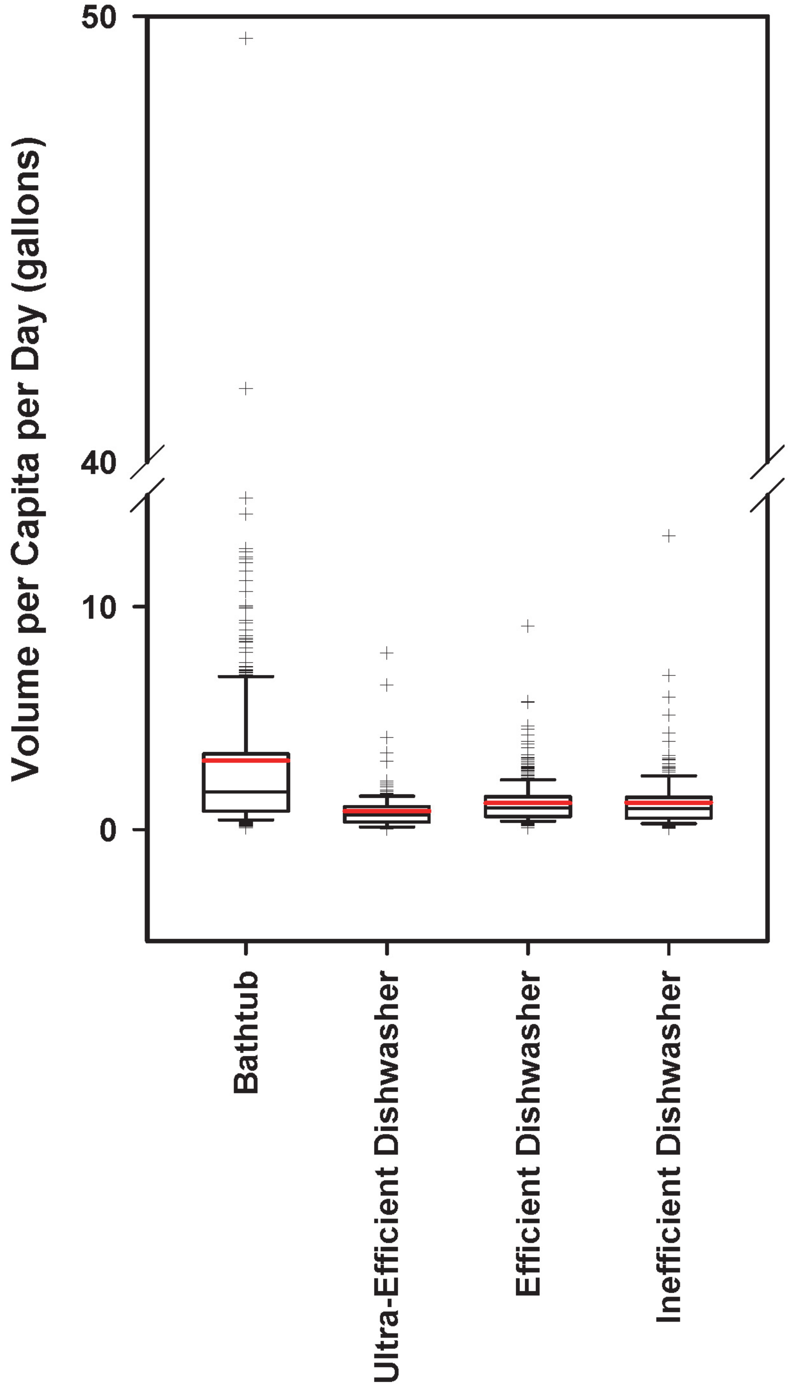


Figure A6: Box and Whisker Plot of the Volume of Water Use Per Capita Per Day for Bathtub and the Different Efficiency Levels Of Dishwasher

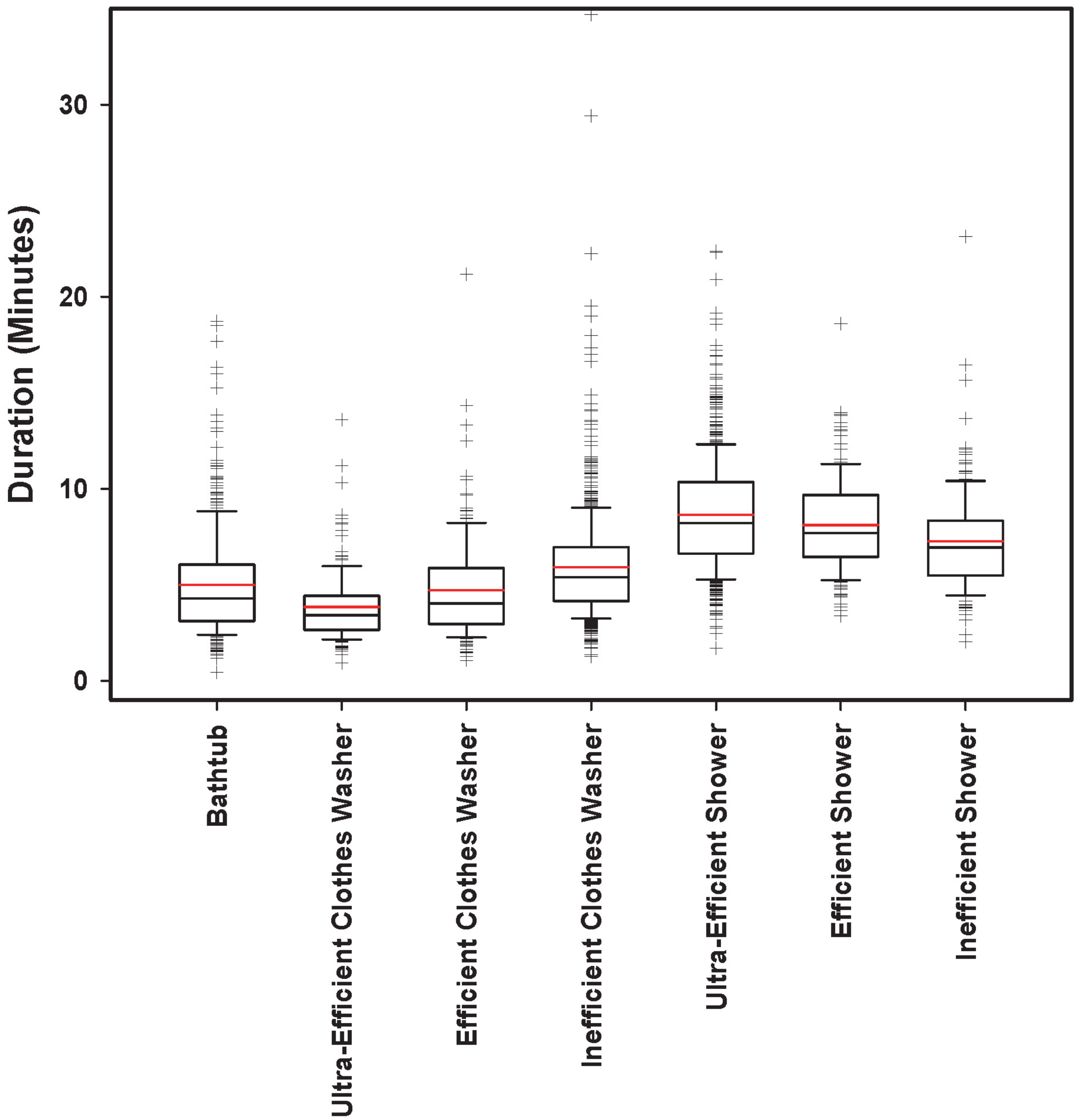


Figure A7: Box and Whisker Plot of the Average Duration of Fixture Use for Bathtub and the Different Efficiency Levels of Clothes Washers and Showers

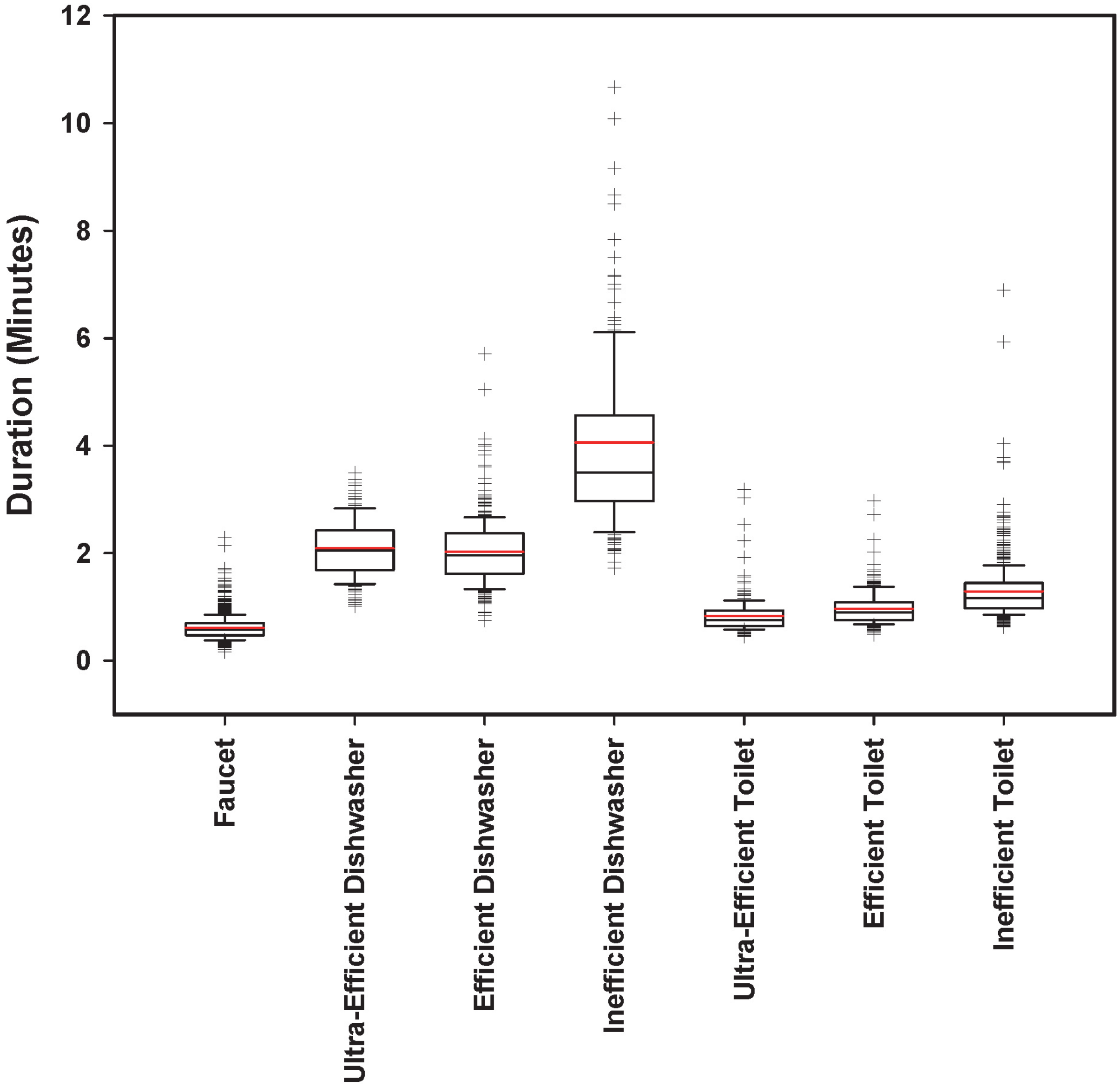


Figure A8: Box and Whisker Plot of the Average Duration of Fixture Use for Faucets and the Different Efficiency Levels of Dishwashers, and Toilets

Table A1: Statistics on Observed Duration of Flow, Volume of Flow, and Flow Rates of Fixture at Various Efficiencies

Fixture	Duration Per use				Volume Per Capita Per Day				Flow rate				Sample Size
	Minimum (minutes)	Maximum (minutes)	Average (minutes)	Standard Deviation (minutes)	Minimum (gallons)	Maximum (gallons)	Average (gallons)	Standard Deviation (gallons)	Minimum (gpm)	Maximum (gpm)	Average (gpm)	Standard Deviation (gpm)	
Ultra-Efficient Fixtures													
Clothes washer	0.94	13.62	3.84	1.85	0.34	32.50	7.29	5.34	0.77	4.30	1.94	0.69	169
Dishwasher	0.75	5.71	1.74	0.53	0.02	7.93	0.83	0.91	0.31	1.58	0.87	0.26	178
Shower	1.69	22.36	8.65	2.92	0.38	142.49	12.11	10.41	0.70	2.20	1.76	0.27	684
Toilet	0.45	3.19	0.84	0.35	0.24	39.09	9.28	5.15	0.43	3.45	2.04	0.53	223
Efficient Fixtures													
Clothes washer	1.07	21.17	4.70	2.66	0.20	52.97	10.44	7.76	0.63	5.84	2.77	0.88	172
Dishwasher	1.10	5.04	2.20	0.56	0.07	9.14	1.19	0.96	0.41	1.87	1.10	0.24	349
Shower	3.38	18.61	8.11	2.46	0.83	39.23	14.18	7.88	2.20	2.50	2.33	0.09	153
Toilet	0.49	2.98	0.97	0.32	0.63	33.48	11.38	5.68	0.73	4.03	2.23	0.59	258
Inefficient Fixtures													
Clothes washer	1.26	34.69	5.91	2.98	0.97	141.40	17.71	14.19	0.68	7.00	3.79	0.95	661
Dishwasher	1.72	25.78	4.06	2.22	0.05	13.18	1.21	1.32	0.44	1.95	1.16	0.27	195
Shower	2.03	23.14	7.26	2.64	0.73	42.02	14.78	9.23	2.50	5.17	3.14	0.56	177
Toilet	0.63	6.89	1.29	0.54	0.57	115.16	19.33	11.96	0.52	5.16	2.78	0.75	556
Unclassified Fixtures													
Bathtub	0.44	18.72	4.99	2.73	0.09	49.51	3.08	4.64	0.96	9.77	4.47	1.22	519
Faucet	0.17	2.29	0.61	0.22	0.13	97.03	11.87	8.78	0.20	1.72	0.97	0.23	1038

Table A2: Characteristics of Fixtures in Surveyed Homes Grouped by the Number of Residents

	Fixtures	Statistics	No. of residents				
			1	2	3	4	5 or more
Efficient Fixtures	Clothes washer	Average fixture/home	1	1	1	1	1
		Sample size (341 homes) (%)	8.8	45.5	19.1	17.6	9.1
		Percentage Ultra-Efficient (%)	43.3	48.4	55.4	56.7	35.5
	Dishwasher	Average fixture/home	1	1.01	1	1	1.04
		Sample size (527 homes) (%)	8.5	44.4	18.6	19	9.5
		Percentage Ultra-Efficient (%)	28.9	32.9	40.8	35	26
	Shower	Average fixture/home	1.82	2.08	2.14	2.3	2.54
		Sample size (837 homes) (%)	11.9	43.6	17	16.8	10.6
		Percentage Ultra-Efficient (%)	78	83	84.5	83	74.2
	Toilet	Average fixture/home	2.02	2.47	2.61	2.66	2.67
		Sample Size (481 homes) (%)	12.9	43.5	17	17.3	9.4
		Percentage Ultra-Efficient (%)	51.6	46.9	45.1	39.8	51.1
Inefficient Fixtures	**Fixtures**		**1**	**2**	**3**	**4**	**5 or more**
	Clothes washer	Average fixture/home	1	1	1	1	1
		Sample size (661 homes) (%)	15.1	43	16.8	15	10.1
	Dishwasher	Average fixture/home	1	1.02	1	1	1
		Sample size (195 homes) (%)	12.8	44.6	19.5	12.3	10.8
	Shower	Average fixture/home	1.58	1.94	2.03	1.81	2.18
		Sample size (177 homes) (%)	14.7	46.9	20.3	11.9	6.2
	Toilet	Average fixture/home	1.97	2.23	2.46	2.53	2.91
		Sample size (556 homes) (%)	13.8	44.6	17.4	14.2	9.9
Unclassified Fixtures	**Fixtures**		**1**	**2**	**3**	**4**	**5 or more**
	Bathtub	Average fixture/home	1.34	1.57	1.56	1.72	2.06
		Sample size (519 homes) (%)	9.1	39.9	17.5	21	12.5
	Faucet	Average fixture/home	3.37	3.79	4	4.1	4.31
		Sample size (1038 homes) (%)	13.4	44.1	17.2	15.6	9.6

Table A3: Statistics on Peak Hour Probability of a Busy Fixture in the Surveyed Homes with Different Fixture Efficiency

Fixture	Minimum	Maximum	Average	Standard Deviation	Sample size	Inactive Homes
Efficient fixtures						
Clothes washer	0.0000	0.3444	0.0198	0.0292	341	108
Dishwasher	0.0000	0.0310	0.0030	0.0052	527	325
Shower	0.0000	0.2405	0.0332	0.0346	837	116
Toilet	0.0000	0.0456	0.0067	0.0052	481	11
Inefficient Fixtures						
Clothes washer	0.0000	0.2525	0.0312	0.0344	661	139
Dishwasher	0.0000	0.0611	0.0029	0.0073	195	147
Shower	0.0000	0.1549	0.0259	0.0241	177	25
Toilet	0.0000	0.0906	0.0108	0.0099	556	15
Unclassified Fixtures						
Bathtub	0.0000	0.1833	0.0052	0.0145	519	314
Faucet	0.0000	0.1044	0.0127	0.0111	1038	9

B – Pipe Sizing Examples

The following examples and steps describe how to use the peak demand estimate from the WDC to determine the pipe size.

Example 1: Indoor Water Use Only

Find the pipe size for the building supply to a one-bathroom residential building with six indoor fixtures, as illustrated in Figure B1. The following information are known.

- Pipe material: L-copper
- Maximum velocity: 8 ft/s
- Friction loss per 100 ft: 15 psi
- Fixture type (number): Combination bath/shower (1), Lavatory faucet (1), Water closet (1), Kitchen faucet (1), Dishwasher (1), and Clothes washer (1)

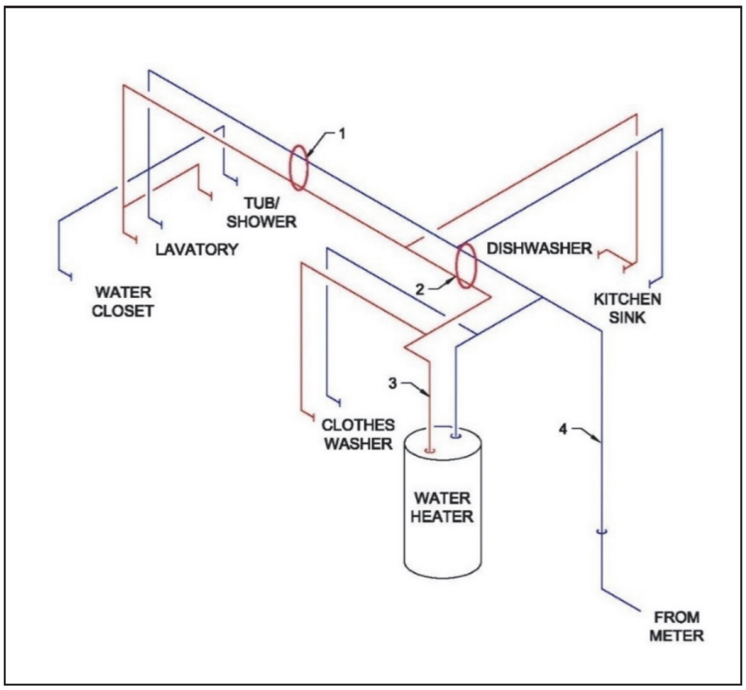
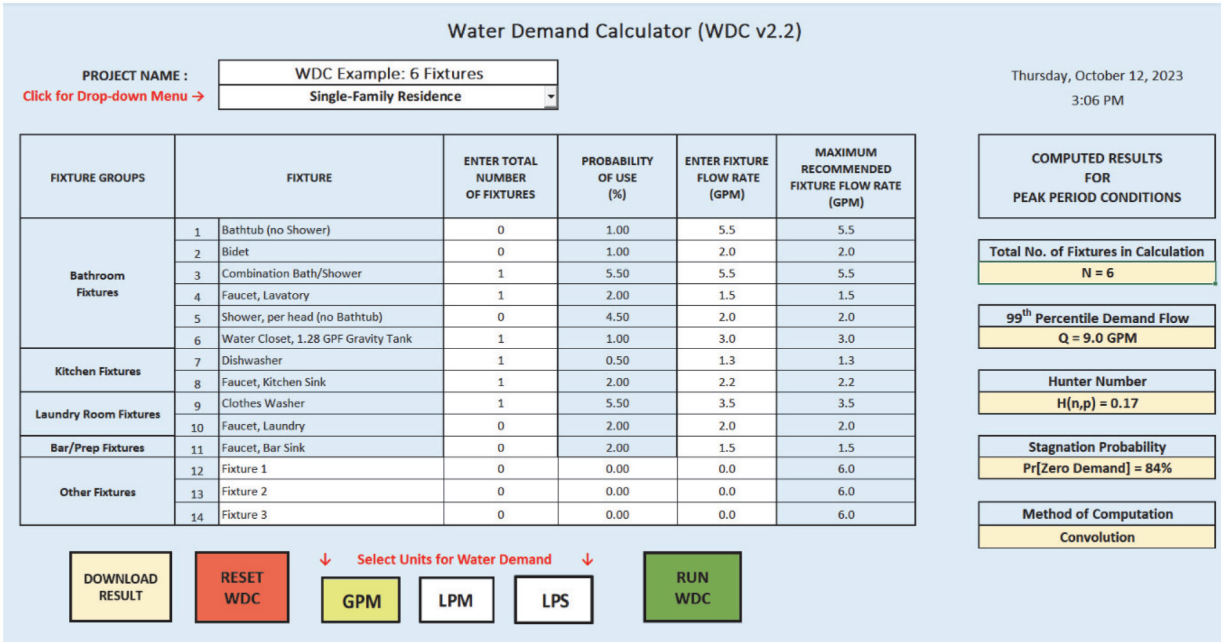


Figure B1: One-Bathroom Residential Building with Six Indoor Fixtures

Solution: Step 1 of 2 – Find Demand Load for the Building Supply

Input the fixture count in the column designated as the total number of fixtures into the Water Demand Calculator (WDC) and click the "**Run WDC"** button to determine the demand load expected from indoor water use. The flow rates in the white cells may be reduced to a lower flow rate for the fixture. As shown in Figure B2, the estimated indoor water demand for the whole building is 9.0 gpm. This result appears in the output box on the right-hand side of the WDC in Figure B2.



Water Demand Calculator (WDC v2.2)

PROJECT NAME : WDC Example: 6 Fixtures

Click for Drop-down Menu → Single-Family Residence

Thursday, October 12, 2023
3:06 PM

FIXTURE GROUPS		FIXTURE	ENTER TOTAL NUMBER OF FIXTURES	PROBABILITY OF USE (%)	ENTER FIXTURE FLOW RATE (GPM)	MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
Bathroom Fixtures	1	Bathtub (no Shower)	0	1.00	5.5	5.5
	2	Bidet	0	1.00	2.0	2.0
	3	Combination Bath/Shower	1	5.50	5.5	5.5
	4	Faucet, Lavatory	1	2.00	1.5	1.5
	5	Shower, per head (no Bathtub)	0	4.50	2.0	2.0
	6	Water Closet, 1.28 GPF Gravity Tank	1	1.00	3.0	3.0
Kitchen Fixtures	7	Dishwasher	1	0.50	1.3	1.3
	8	Faucet, Kitchen Sink	1	2.00	2.2	2.2
Laundry Room Fixtures	9	Clothes Washer	1	5.50	3.5	3.5
	10	Faucet, Laundry	0	2.00	2.0	2.0
Bar/Prep Fixtures	11	Faucet, Bar Sink	0	2.00	1.5	1.5
Other Fixtures	12	Fixture 1	0	0.00	0.0	6.0
	13	Fixture 2	0	0.00	0.0	6.0
	14	Fixture 3	0	0.00	0.0	6.0

COMPUTED RESULTS FOR PEAK PERIOD CONDITIONS

Total No. of Fixtures in Calculation: N = 6

99th Percentile Demand Flow: Q = 9.0 GPM

Hunter Number: H(n,p) = 0.17

Stagnation Probability: Pr[Zero Demand] = 84%

Method of Computation: Convolution

DOWNLOAD RESULT | RESET WDC | ↓ Select Units for Water Demand ↓ | GPM | LPM | LPS | RUN WDC

Figure B2. Example 1, WDC Input for Indoor Use at Home with Six Efficient Fixtures

Solution: Step 2 of 2 – Determine the Pipe Size of the Building Supply

Figure B3 (Chart A 105.1(1) from Appendix A of the UPC) for Type L-copper piping systems is used to determine the pipe size based on given friction loss, given maximum allowable pipe velocity, given pipe material, and the demand load computed in Step 1. Figure B3 shows the intersection of the given friction loss (15 psi) and the maximum allowable pipe velocity (8 ft/s) labeled point **A**. The line that descends from point A to the base of the chart intersects four nominal sizes for L-copper pipe. These intersection points are labeled B, C, D, and E and correspond to pipe sizes of 1 inch (25 mm), 3/4 inch (20 mm), ½ inch (15 mm) and 3/8 inch (10 mm), respectively. A horizontal line from points **B**, **C**, **D**, and **E** to the right-hand side of the chart gives maximum flow rates of 20 gpm, 12 gpm, 4.5 gpm, and 2.3 gpm, respectively. These results are summarized in Table B1, which shows that a ¾ inch (20 mm) type L copper line is the minimum size that can convey the peak water demand of 9.0 gpm.

Table B1: Pipe Size Options for Building Supply

Point in Figure B1	Pipe Diameter (inch)	Maximum Flow (GPM)	OK for Building Supply?[1]
E	3/8	2.3	No
D	1/2	4.5	No
C	3/4	12	Yes
B	1	20	Yes

[1.] For Building in examples 1, 2, 3, and 4.

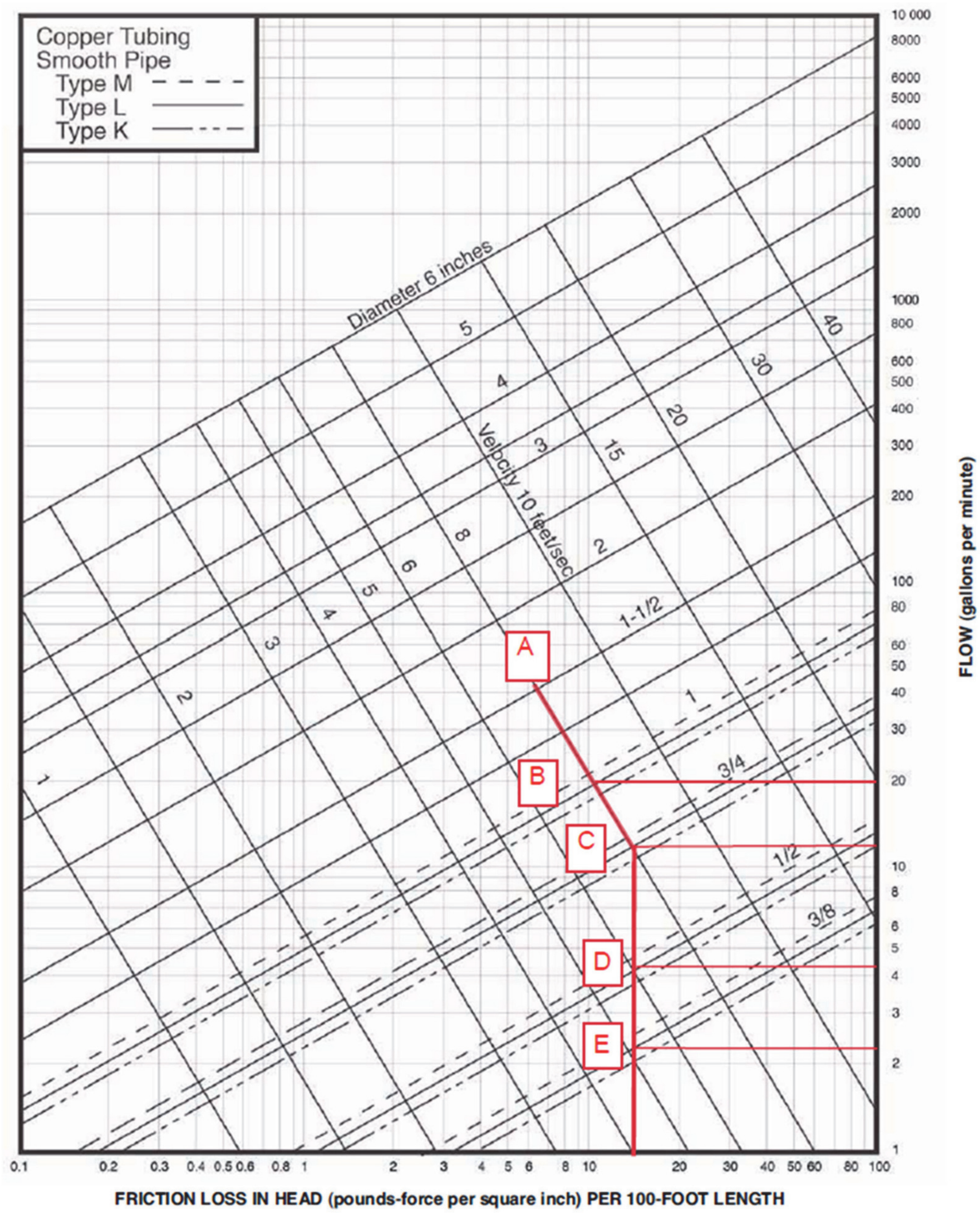


Figure B3: Chart A 105.1(1) for Finding Pipe Size

Example 2: Indoor and Outdoor Water Use

Find the pipe size for the building supply [Figure B1, Pipe Section 4] if the building in Example 1 has two additional outdoor fixtures (i.e., hose bibb, each with a fixture flow of 4.0 gpm).

Solution: Step 1 of 2 – Find Demand Load for the Building Supply

The WDC was developed exclusively for peak indoor water use, which can be viewed as high-frequency, short-duration events. Because fixtures for outdoor water use may operate continuously for very long periods, they are <u>not</u> included in the WDC calculations. To account for water use from one or more outdoor fixtures, add the demand of the single outdoor fixture with the highest flow rate to the calculated demand for indoor water use. Therefore, with two hose bibbs, the demand for one hose bibb is added to the indoor demand. Hence, in this example, the total demand for the whole house is 9.0 gpm + 4.0 gpm = 13.0 gpm.

Solution: Step 2 of 2 – Determine the Pipe Size of the Building Supply

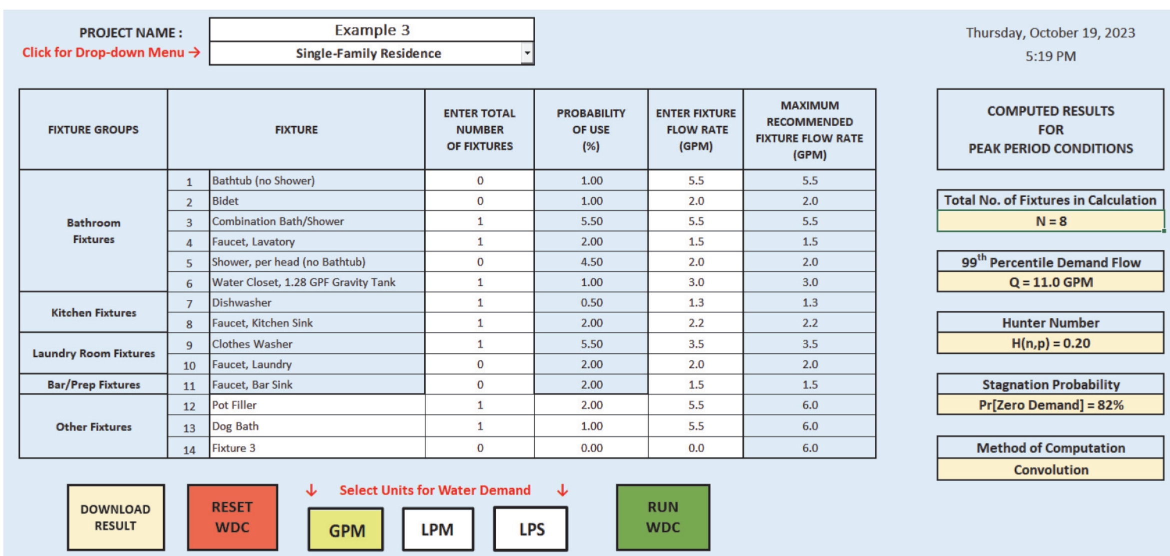
Table B1 shows that at 13.0 gpm, the building supply, including outdoor water use, shall be 1-inch in diameter.

Example 3: Indoor, Outdoor, and Other Fixture Water Use

Find the pipe size for the water supply [Figure B1, Pipe Section 4] if the building in Example 2 adds a kitchen pot filler and a dog bath, each with a faucet flow rate of 5.5 gpm.

Solution: Step 1 of 2 – Find Demand Load for the Building Supply

The kitchen pot filler and dog bath are not listed as a type of fixture in the WDC. The WDC provides up to three additional rows for "Other Fixtures" to accommodate cases like this. Enter the kitchen pot filler and dog bath in the fixture list column of the WDC and enter the fixture count for each in the next column. Find an indoor fixture that has a similar probability of use and input as the fixture probability of use. Finally, enter the flow rate of the kitchen pot filler and dog bath. The estimated indoor water demand for the building is 11 gpm, as shown in the WDC in Figure B4. As illustrated in Example 2, adding the hose bibb to this example will increase the total demand for the whole house to 15 gpm.



FIXTURE GROUPS		FIXTURE	ENTER TOTAL NUMBER OF FIXTURES	PROBABILITY OF USE (%)	ENTER FIXTURE FLOW RATE (GPM)	MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
Bathroom Fixtures	1	Bathtub (no Shower)	0	1.00	5.5	5.5
	2	Bidet	0	1.00	2.0	2.0
	3	Combination Bath/Shower	1	5.50	5.5	5.5
	4	Faucet, Lavatory	1	2.00	1.5	1.5
	5	Shower, per head (no Bathtub)	0	4.50	2.0	2.0
	6	Water Closet, 1.28 GPF Gravity Tank	1	1.00	3.0	3.0
Kitchen Fixtures	7	Dishwasher	1	0.50	1.3	1.3
	8	Faucet, Kitchen Sink	1	2.00	2.2	2.2
Laundry Room Fixtures	9	Clothes Washer	1	5.50	3.5	3.5
	10	Faucet, Laundry	0	2.00	2.0	2.0
Bar/Prep Fixtures	11	Faucet, Bar Sink	0	2.00	1.5	1.5
Other Fixtures	12	Pot Filler	1	2.00	5.5	6.0
	13	Dog Bath	1	1.00	5.5	6.0
	14	Fixture 3	0	0.00	0.0	6.0

Figure B4: Example 3, WDC Input Accommodating Other Fixtures

Solution: Step 2 of 2 – Determine the Pipe Size of the Building Supply

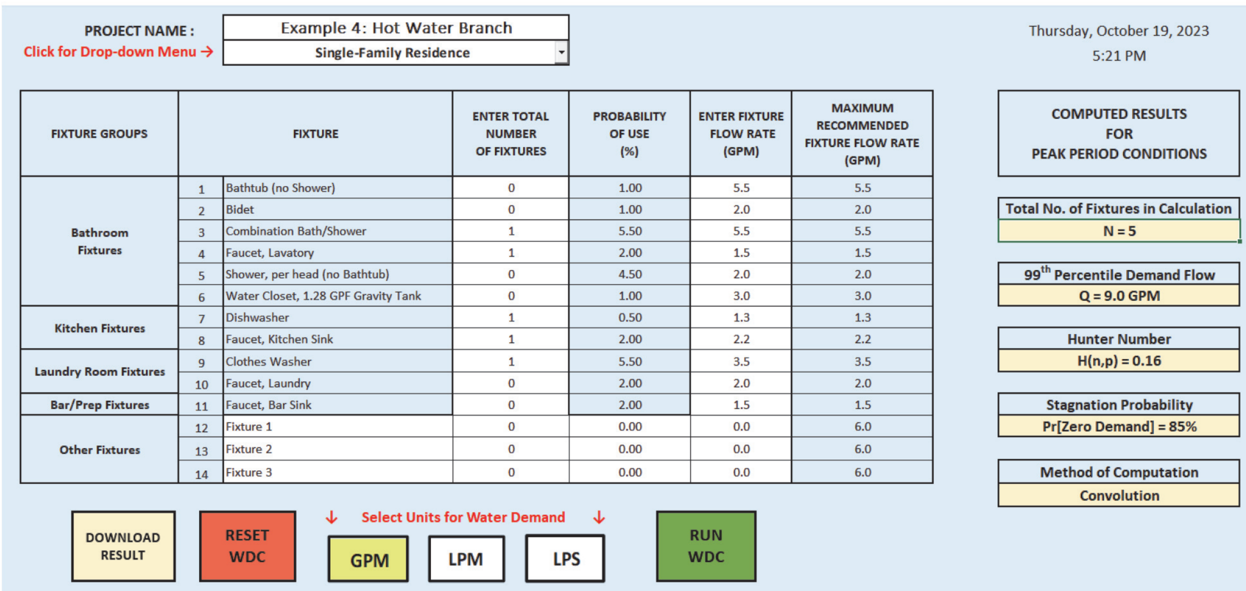
Table B1 shows that at 15 gpm, the building supply shall be 1 inch in diameter.

Example 4: Sizing Branches and Risers

For individual hot and cold branches, repeat Steps 1 and 2. For example, for the hot water branch at the water heater [Figure B1, Pipe Section 3], enter all the fixtures and appliances that use hot water into the Water Demand Calculator (toilets will be excluded), as seen in Figure B5. Use the calculated demand load to find the pipe size in Step 2. Table B1 shows that at 9.0 gpm, the hot water branch shall be ¾-inch in diameter.

For each additional hot and cold branch [Figure B1, Pipe Sections 1 and 2], enter the number of fixtures and appliances served by that branch into the WDC and use that demand in Step 2 to determine the branch size. If the branch serves a hose bibb, add the demand of the hose bibb to the calculated demand flow for the branch. As discussed in Example 2, the hose bibb will not be entered into WDC since the Calculator is only for indoor uses.

When only one fixture or appliance is served by a fixture branch, the demand flow shall not exceed the fixture flow rate in the last column of the Water Demand Calculator. The fixture flow rate will be used in Step 2 to determine the size of the fixture branch and supply.



PROJECT NAME : Example 4: Hot Water Branch

Click for Drop-down Menu → Single-Family Residence

Thursday, October 19, 2023
5:21 PM

FIXTURE GROUPS		FIXTURE	ENTER TOTAL NUMBER OF FIXTURES	PROBABILITY OF USE (%)	ENTER FIXTURE FLOW RATE (GPM)	MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
Bathroom Fixtures	1	Bathtub (no Shower)	0	1.00	5.5	5.5
	2	Bidet	0	1.00	2.0	2.0
	3	Combination Bath/Shower	1	5.50	5.5	5.5
	4	Faucet, Lavatory	1	2.00	1.5	1.5
	5	Shower, per head (no Bathtub)	0	4.50	2.0	2.0
	6	Water Closet, 1.28 GPF Gravity Tank	0	1.00	3.0	3.0
Kitchen Fixtures	7	Dishwasher	1	0.50	1.3	1.3
	8	Faucet, Kitchen Sink	1	2.00	2.2	2.2
Laundry Room Fixtures	9	Clothes Washer	1	5.50	3.5	3.5
	10	Faucet, Laundry	0	2.00	2.0	2.0
Bar/Prep Fixtures	11	Faucet, Bar Sink	0	2.00	1.5	1.5
Other Fixtures	12	Fixture 1	0	0.00	0.0	6.0
	13	Fixture 2	0	0.00	0.0	6.0
	14	Fixture 3	0	0.00	0.0	6.0

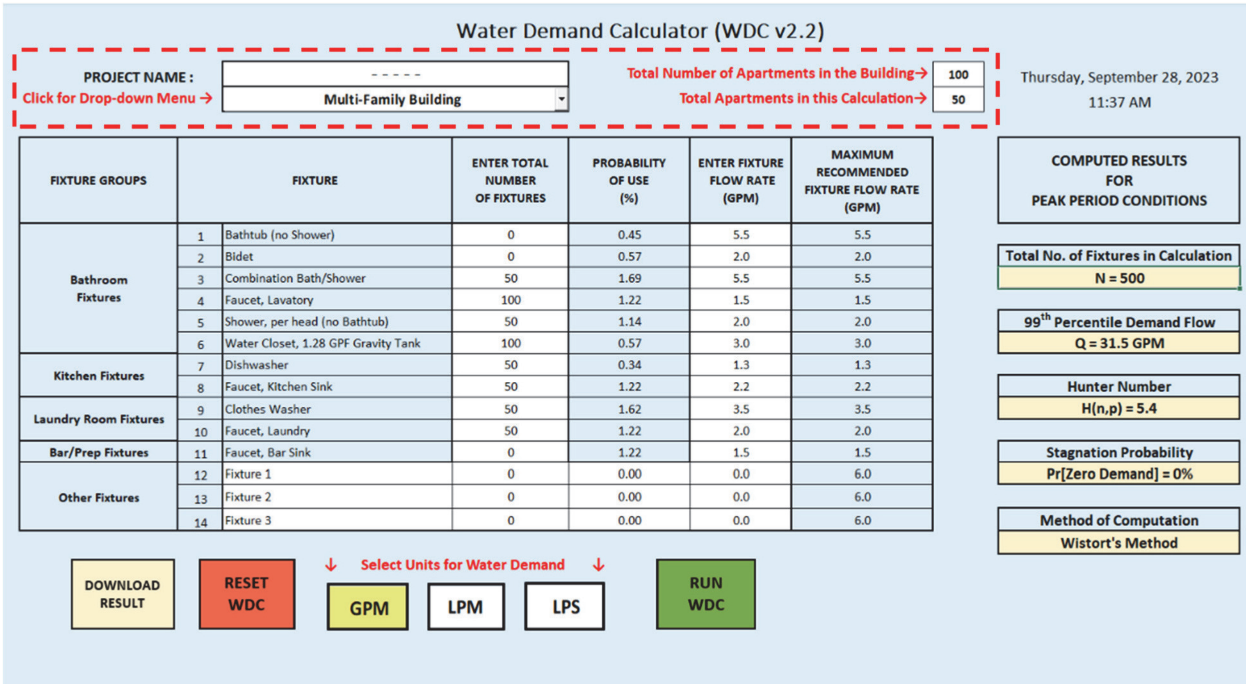
COMPUTED RESULTS FOR PEAK PERIOD CONDITIONS

Total No. of Fixtures in Calculation	N = 5
99^{th} Percentile Demand Flow	Q = 9.0 GPM
Hunter Number	H(n,p) = 0.16
Stagnation Probability	Pr[Zero Demand] = 85%
Method of Computation	Convolution

Figure B5. Example 4, WDC Input for the Hot Water Branch in a Single-Family Residence

Example 5: Multi-family Application

When using the WDC for multi-family dwellings, use the drop-down menu on the top left corner to select "single-family residence" or "multi-family building". Choosing the multi-family option opens two more boxes to fill in the information (See Figure B6). When estimating peak demand for a multi-family building, enter the total number of dwelling units. The example shows a total of 100 dwelling units in the building. The box below will be for the number of units you are calculating for. If you are calculating for the whole building, enter the same number of 100. If you are calculating for half the dwelling units, enter 50. If estimating for only one unit, enter the number one. The total number of dwelling units in the first box will not change in your calculations. Then, use the WDC, as explained earlier, to size branches and risers.



Water Demand Calculator (WDC v2.2)

PROJECT NAME : - - - - -

Click for Drop-down Menu → Multi-Family Building

Total Number of Apartments in the Building→ 100

Total Apartments in this Calculation→ 50

Thursday, September 28, 2023

11:37 AM

FIXTURE GROUPS		FIXTURE	ENTER TOTAL NUMBER OF FIXTURES	PROBABILITY OF USE (%)	ENTER FIXTURE FLOW RATE (GPM)	MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
Bathroom Fixtures	1	Bathtub (no Shower)	0	0.45	5.5	5.5
	2	Bidet	0	0.57	2.0	2.0
	3	Combination Bath/Shower	50	1.69	5.5	5.5
	4	Faucet, Lavatory	100	1.22	1.5	1.5
	5	Shower, per head (no Bathtub)	50	1.14	2.0	2.0
	6	Water Closet, 1.28 GPF Gravity Tank	100	0.57	3.0	3.0
Kitchen Fixtures	7	Dishwasher	50	0.34	1.3	1.3
	8	Faucet, Kitchen Sink	50	1.22	2.2	2.2
Laundry Room Fixtures	9	Clothes Washer	50	1.62	3.5	3.5
	10	Faucet, Laundry	50	1.22	2.0	2.0
Bar/Prep Fixtures	11	Faucet, Bar Sink	0	1.22	1.5	1.5
Other Fixtures	12	Fixture 1	0	0.00	0.0	6.0
	13	Fixture 2	0	0.00	0.0	6.0
	14	Fixture 3	0	0.00	0.0	6.0

COMPUTED RESULTS FOR PEAK PERIOD CONDITIONS

Total No. of Fixtures in Calculation

N = 500

99th Percentile Demand Flow

Q = 31.5 GPM

Hunter Number

H(n,p) = 5.4

Stagnation Probability

Pr[Zero Demand] = 0%

Method of Computation

Wistort's Method

DOWNLOAD RESULT

RESET WDC

↓ Select Units for Water Demand ↓

GPM LPM LPS

RUN WDC

Figure B6. Example 5, WDC Input for Multi-family Building

C – Task Group Members

Daniel Cole (Task Group Chair) is the Sr. Director of Technical Services and Research at IAPMO. He was a licensed Journeyman Plumber, Contractor, Inspector, and Plan Reviewer in the State of Illinois. He is a member of the American Society of Plumbing Engineers (ASPE). He has published several articles on Hunter's curve and the fixture unit methodology. His research focuses on the plumbing investigations performed at the National Bureau of Standards (now NIST) with a particular focus on the work of Roy B. Hunter.

Steven Buchberger, Ph.D., is a Professor Emeritus at the University of Cincinnati. He is a registered professional engineer in Colorado. His teaching and research focus on reliability-based design in water resources and urban hydrology. Professor Buchberger has advised 60 graduate students at UC. He served as Associate Editor of ASCE Journal of Water Resources Planning and Management for ten years and was the Chief Editor of two special issues on Water Distribution Systems Analysis.

Jason Hewitt is a professional engineer with 17 years of experience designing high-rise buildings along the west coast. He currently works for CB Engineers as the Seattle office manager. He is a founding member of the Seattle ASPE Chapter and served on the board as VP of Technical and VP Legislative from 2010 - 2015.

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