Estimating Water Demand

What are the Chances?

Cautious risk-takers and gamers want to know the odds of winning or losing before investing or laying a bet. Of course, you have the extremes of those who throw all caution to the wind and gamble away their money, and those who take no risks at all, wanting that 100 percent certainty of success before making a move. Solving problems regarding games of chance for the cautious risk-takers have occupied mathematicians since the 17th century. Christian Huygens, Pierre Remond de Montmort, and Jakob Bernoulli are famous for publishing mathematical solutions relating to doctrines of chance that launched a new mathematical trajectory of probability and statistics. Before laying their money down, gamers and risk-takers wanted to know their chances for winning and the odds of losing and they would send their inquiries to the mathematicians. Card theory, slot machines, roulette, craps, poker, and 21 all became subject to the burgeoning principles of probability.

Gaming was not the only application for mathematical probability. Today, probability and statistics have spread throughout the world of business, industry, manufacturing, sports, SATs, medicine, insurance, and wherever there is the need to predict outcomes. Oddly enough, even plumbing benefited from principles of probability. When designing a plumbing system, is there a need to predict an outcome? Is there a chance of failure if the system is not designed properly? Are there risks associated with improperly sizing a plumbing system? Is there a way to know the odds on whether the system design will be a success or failure? Is guesstimating throwing caution to the wind, or should systems be designed with a 100 percent certainty basing the expected outcome on every fixture and appliance operating simultaneously every time?

Prior to the 1920s there was no uniformity on how to estimate the water supply demand needed for a building or knowing the minimum supply pipe size. Generally, it was a guess, and the pipe was generously sized to meet any demand. Pipe sizes and costs of material could be reduced if a peak demand could be calculated and applied to the supply pipe. A peak demand would only include fixtures that would be on simultaneously. What calculation would determine that? If the problem was framed as a question asking what are the chances of more than one fixture being on at the same time, the solution involves mathematical probability.

Applying principles of probability to the design of the plumbing system was first introduced by Roy B. Hunter in a 1923 National Bureau of Standards publication, *Recommended Minimum Requirements for Plumbing in Dwellings and Similar Buildings*. Originally applied for the drainage system, he later refined the principles of probability when applied to the water distribution system in a 1940 publication, *Methods of Estimating Loads in Plumbing Systems*. Since that time, all plumbing codes in the U.S. and even abroad adopted the method of probabilities developed by Hunter for estimating the demand loads for water distribution systems.

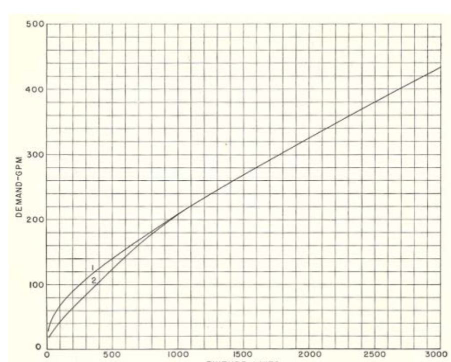
What was Hunter doing and how was he applying principles of probability to the plumbing system? Which outcome was he trying to predict? Were there odds of failure?

Hunter was trying to eliminate the tendency for oversizing the water distribution system in cases where there were many fixtures in larger buildings, which was more of a rule-of-thumb procedure (guesstimate) resulting in a too large an estimate. The principles of probability would more accurately predict the estimated outcome of how many fixtures out of a total number of fixtures would be operating at the same time. Designing a water distribution system based on a predicted outcome is an estimation of peak demand. Peak demand is the predicted number of fixtures (let's call this number *x*) out of a total number of fixtures (let's call this number *n*) that are expected to be drawing from the water supply at the same time. The water supply would be designed for the peak demand of the number of *x* fixtures and not the total number of *n* fixtures.

To predict this *x* value, Hunter applied the Bernoulli trial, the law of combinations, and the binomial distribution. A Bernoulli trial is one that has only two possible outcomes. In the case of plumbing fixtures and appliances, the only two possible outcomes are that the fixture is either on or off. The probability (p) that a fixture is on is determined by t/T, where t is the duration of time that water is flowing through the fixture when it is on, and T is the time in between the use of the fixture when the fixture is off. Suppose a tank-type toilet takes five seconds to fill after a flush, and that it is used every 300 seconds (five minutes) during a busy time. The probability that the toilet fixture is on is .02 (5/300).

The law of combinations was applied to the number of ways in which two or more independent events can occur together at the same instant of observation. This accounts for random selection. Suppose there is a battery of six toilets. How many ways can two independent toilets flush together at the same time? The mathematical expression is $C\binom{6}{2}$ = 15. There are 15 different ways to combine two independent toilets out of a total number of 6 toilets.

The binomial distribution models the probability distribution of the number of successes in a sequence of independent outcomes for a given sample size. The mathematical formula gets a little more complicated and is expressed as $\Pr\left[x\ busy\ \ fixtures \middle| n, p\right] = \binom{n}{x}(p)^x(1-p)^{n-x} \qquad x = 0,1,\ldots,n$. This formula will tell you the probability of a number of x fixtures that would be on at the same time out of a total of n fixtures. Suppose there were a total number of 30 toilets each having a probability of .03 of being on. What is the probability of two toilets flushing at the same time? The binomial distribution predicts .17 or a 17% chance. What is the probability of three toilets flushing at the same time? The equation predicts .05 or 5%. The probability of four toilets flushing simultaneously is .01 or 1%. Which outcome do you select? The 17%, 5% or the 1% outcome? Hunter chose the number of successes at the 1% outcome. This means that you would design the water supply for the demand of only four toilets rather than the total number of 30 toilets, a substantial savings at a very low risk of failure.



Using the number of successes at the 1% outcome, Hunter developed a binomial distribution curve for design purposes. This was a boon for the plumbing industry and was universally adopted in plumbing codes throughout the U.S. for water supply estimating and pipe sizing.

Hunter's method worked well for 30 years until criticism arose among practicing engineers that the curve estimates were excessive, causing the system to be oversized. Even though variations in decreasing the value of fixture units have been applied in plumbing codes, systems were still overestimated. Sparsity of field data prevented any improvement to modify the parameters of the probability model.

What were the reasons for the curve estimates to become excessive 30 years later? There were two things occurring over the years since the 1940s. Plumbing fixtures and appliances were becoming more efficient with lower water consumption. Secondly, the frequency of use for the same kind of fixture varied significantly in different building types as modern building design and occupancy became more diversified. In other words, the Bernoulli trial mentioned above (t/T), which determined the probability of when a fixture is on, was no longer constant in every building classification. It was only applicable when the frequency of use was under congested conditions where people in queue were waiting to use a fixture, one following the other user.

Furthermore, government policies such as the Energy Policy Act (EPAct) of 1992, which mandated water conservation for plumbing fixtures, and the EPA WaterSense program, which recommends water reductions by 20% lower than EPAct, exacerbated over estimating peak demand when using Hunter's design curve. States experiencing the problem of draught and water scarcity are still resolving to further reduce water consumption for plumbing fixtures.

IAPMO now offers a solution to the problem of overestimating, having developed a new Water Demand Calculator for estimating water supply demand for residential single and multifamily dwellings. This new method will be published in the IAPMO/ANSI *We•Stand 2017* and the 2018 *Uniform Plumbing Code* in the appendices of both American National Standards.

New probability computations are brought into the 21st century through a programmed MS Excel spreadsheet with a table of plumbing fixtures and appliances most commonly found in residential dwellings. The parameters for a probability distribution appear in Columns [B], [C], and [D]. Notice the fixture flow rates are for water-conserving plumbing fixtures and appliances, and the values may be reduced as actual fixture flow rates are being reduced. The probability of fixture use was derived from the largest U.S. database for residential end use of water survey. To use this spreadsheet for estimating peak water supply demand loads, enter the number of fixtures and appliances in Column [B] and click on the box that says Run Water Demand Calculator. The estimated demand flow will automatically be calculated in the green box. The results will be more definite than using a curve and trying to match the exact (x,y) ordinates on the curve with the corresponding flow rate.

	[A] FIXTURE	[B] ENTER NUMBER OF FIXTURES	[C] PROBABILITY OF USE (%)	[D] ENTER FIXTURE FLOW RATE (GPM)	[E] MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
1	Bar Sink	0	2.0	1.5	1.5
2	Bathtub	0	1.0	5.5	5.5
3	Bidet	0	1.0	2.0	2.0
4	Clothes Washer	0	5.5	3.5	3.5
5	Combination Bath/Shower	0	5.5	5.5	5.5
6	Dishwasher	0	0.5	1.3	1.3
7	Kitchen Faucet	0	2.0	2.2	2.2
8	Laundry Faucet	0	2.0	2.0	2.0
9	Lavatory Faucet	0	2.0	1.5	1.5
10	Shower, per head	0	4.5	2.0	2.0
11	Water Closet, 1.28 GPF Gravity Tank	0	1.0	3.0	3.0
12	Other Fixture 1	0	0.0	0.0	6.0
13	Other Fixture 2	0	0.0	0.0	6.0
14	Other Fixture 3	0	0.0	0.0	6.0
	Total Number of Fixtures	0			

99th PERCENTILE DEMAND FLOW = GPM

RESET

RUN WATER DEMAND CALCULATOR

↑ CLICK BUTTON ↑

Title Page | Key | DemandEstimate

Ready 70%

Place your Number

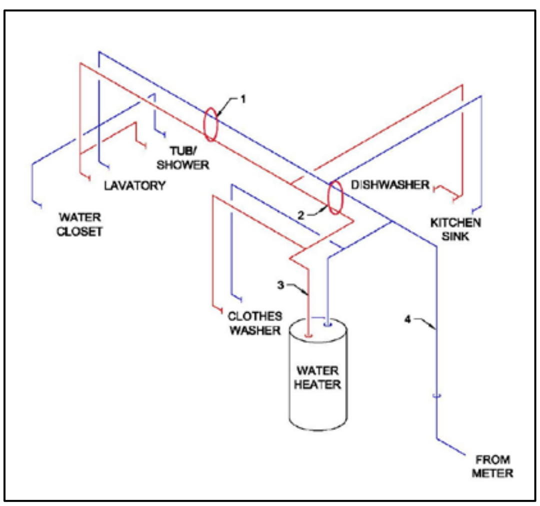
We all love simplicity. Simplicity saves time, reduces the margin of error, promotes broader applicability, and is user-friendly. Students today love the simplified "plug and chug" math. This is when you have a ready-made formula complete with the X and Y variables. All you have to do is substitute the

X and Y with the right numbers and chug away at the math. Better yet, if you have the formula programmed in your graphing calculator, you just plug in the numbers and let the calculator do the chugging for you.

This is what the Water Demand Calculator provides for plumbing system designers. We have already seen a binomial formula that was a bit complicated, and would intimidate those less savvy with numbers from attempting to use. Simplicity was key when choosing an MS Excel spreadsheet as a calculator, where you only need to place your number in the assigned cell and let the calculator produce the odds.

There are four formulas programmed in the Excel spreadsheet. The calculator will select only one formula based on the numbers you place in the spreadsheet. It will then evaluate the number for each kind of fixture with its corresponding frequency of use (the p-value), sum up the values, and place that value within a range determined for one of the formulas. Once the formula is chosen, it chugs out the math and places the answer in the Demand Flow box within seconds. Seriously, all you have to do is place your number and you are guaranteed the winning answer.

Are you ready to place your number? Let's try this out. If you downloaded the calculator using the link provided at the end of this article, then open it up and follow along. The Figure below shows a residential home with one bathroom, kitchen, and clothes washer. First, let's estimate the demand for the whole house at Pipe Section 4. Notice there are six indoor fixtures – a lavatory, combination bath/shower, water closet, kitchen faucet, dishwasher, and clothes washer. Since there is only one of each, place the number 1 in Column [B] after each of the six fixtures in the Water Demand Calculator. After doing so, click on the box that says Run Water Demand Calculator. The estimated demand for the whole house will appear in the Demand Flow box. In this example, the estimated demand for the whole house is 8.5 gpm.



	[A] FIXTURE	[B] ENTER NUMBER OF FIXTURES	[C] PROBABILITY OF USE (%)	[D] ENTER FIXTURE FLOW RATE (GPM)	[E] MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
1	Bar Sink	0	2.0	1.5	1.5
2	Bathtub	0	1.0	5.5	5.5
3	Bidet	0	1.0	2.0	2.0
4	Clothes Washer	1	5.5	3.5	3.5
5	Combination Bath/Shower	1	5.5	5.5	5.5
6	Dishwasher	1	0.5	1.3	1.3
7	Kitchen Faucet	1	2.0	2.2	2.2
8	Laundry Faucet	0	2.0	2.0	2.0
9	Lavatory Faucet	1	2.0	1.5	1.5
10	Shower, per head	0	4.5	2.0	2.0
11	Water Closet, 1.28 GPF Gravity Tank	1	1.0	3.0	3.0
12	Other Fixture 1	0	0.0	0.0	6.0
13	Other Fixture 2	0	0.0	0.0	6.0
14	Other Fixture 3	0	0.0	0.0	6.0
	Total Number of Fixtures	6			

99th PERCENTILE DEMAND FLOW = 8.5 GPM

RESET

RUN WATER DEMAND CALCULATOR

Easy enough? Let's try some branch sizing. First, click the Reset button in the Calculator and it will clear Column [B] of the previous numbers you entered. Let's estimate the demand for the hot water branch at the water heater, Pipe Section 3 in isometric example. The water closet is the only fixture that does not use hot water, so it would be excluded in the calculator. Enter the number 1 after the other five fixtures and then click Run Water Demand Calculator. The estimated demand for the hot water branch at the water heater is 7.7 gpm.

	[A] FIXTURE	[B] ENTER NUMBER OF FIXTURES	[C] PROBABILITY OF USE (%)	[D] ENTER FIXTURE FLOW RATE (GPM)	[E] MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
1	Bar Sink	0	2.0	1.5	1.5
2	Bathtub	0	1.0	5.5	5.5
3	Bidet	0	1.0	2.0	2.0
4	Clothes Washer	1	5.5	3.5	3.5
5	Combination Bath/Shower	1	5.5	5.5	5.5
6	Dishwasher	1	0.5	1.3	1.3
7	Kitchen Faucet	1	2.0	2.2	2.2
8	Laundry Faucet	0	2.0	2.0	2.0
9	Lavatory Faucet	1	2.0	1.5	1.5
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11	Water Closet, 1.28 GPF Gravity Tank	0	1.0	3.0	3.0
12	Other Fixture 1	0	0.0	0.0	6.0
13	Other Fixture 2	0	0.0	0.0	6.0
14	Other Fixture 3	0	0.0	0.0	6.0
	Total Number of Fixtures	5			
	99th PERCENTILE DEMAND FLOW =	7.7	GPM	RESET	RUN WATER DEMAND CALCULATOR

Now let's do a couple on your own for those who downloaded the calculator. Pipe Section 2 in Figure 1 shows a cold and hot water branch. To estimate the cold branch demand, enter the number 1 in Column [B] after the kitchen faucet, the combination bath/shower, lavatory, and water closet. These are the fixtures that use cold water. The dishwasher is excluded. Click Run Water Demand Calculator. What is your answer? The cold water branch at Pipe Section 2 has an estimated demand of 7.7 gpm. Now do the hot water demand estimate at Pipe Section 2. Did you exclude the water closet and include the dishwasher? The hot water branch has an estimated demand of 7.0 gpm.

As the number of fixtures on a branch is reduced to one fixture, the remaining fixture supply has a flow rate dictated by that fixture. For example, a fixture supply to a lavatory faucet has a flow rate of 1.5 gpm. There is no need to put a single fixture in the calculator, but if you do, the result will just be the flow rate for that single fixture.

Hopefully you've got the hang of this, and now I can introduce some more features of the Water Demand Calculator. By observing the fixture flow rates in Column [D] you may have guessed that these flow rates are for water-conserving fixtures. Notice also that there are blue-colored and white-colored cells. The blue-colored cells are fixed and can't be changed, but you can change the values in the white-colored cells. However, the flow rates in Column [D] can only be decreased and not increased, depending on the actual flow rate of the water-conserving fixture.

In Column [A] there are additional rows for Other Fixture not included in the calculator. For example, you can add a pot filler and a dog bath to the list of fixtures. When doing this, find an indoor fixture that has a similar probability of use in Column [C] and add that to the column. Then enter the actual flow rate of additional fixtures in Column [D]. Then click Run Water Demand Calculator. Adding these fixtures slightly increased the estimated demand of the whole house.

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1	Bar Sink	0	2.0	1.5	1.5
2	Bathtub	0	1.0	5.5	5.5
3	Bidet	0	1.0	2.0	2.0
4	Clothes Washer	1	5.5	3.5	3.5
5	Combination Bath/Shower	1	5.5	5.5	5.5
6	Dishwasher	1	0.5	1.3	1.3
7	Kitchen Faucet	1	2.0	2.2	2.2
8	Laundry Faucet	0	2.0	2.0	2.0
9	Lavatory Faucet	1	2.0	1.5	1.5
10	Shower, per head	0	4.5	2.0	2.0
11	Water Closet, 1.28 GPF Gravity Tank	1	1.0	3.0	3.0
12	Pot Filler	1	2.0	3.0	6.0
13	Dog Bath	1	1.0	5.5	6.0
14	Other Fixture 3	0	0.0	0.0	6.0
	Total Number of Fixtures	8			
	99th PERCENTILE DEMAND FLOW =	9.0	GPM	RESET	RUN WATER DEMAND CALCULATOR

There is one caveat that must be observed. The fixtures and appliances applicable to the Water Demand Calculator are those that have an indoor residential frequency-of-use pattern that are recurrent or intermittent. Outdoor water uses such as hose bibbs and landscape irrigation are too variable and infrequent to have an intermittent or recurrent frequency of use. Such water draws are on for a long duration of time and then off for long periods of time, and are considered continuous flows. Continuous flow fixtures are not to be entered into the Water Demand Calculator as Other Fixtures. Rather, continuous flows (in gpm) are to be added to the Demand Flow estimate. For example, Figure 2 shows the whole house demand flow of 8.5 gpm. If there is a hose bibb with a flow rate of 2.0 gpm, then 2.0 gpm would be added to 8.5 gpm for a total whole house estimated demand of 10.5gpm.

The Water Demand Calculator was purposely developed for water-conserving fixtures and appliances. Hence, high-flow Roman tub fillers (exceeding the bathtub flow rates in Column [E] of the calculator) and luxury shower spas fall outside the calculator's scope. These also should not be included in the Water Demand Calculator, but considered similar to continuous flow fixtures with the high flow rates added to the estimated demand from the Water Demand Calculator.

Now that you know how to use the Water Demand Calculator to find the estimated demand for each pipe segment of a water distribution system, how do you go from the flow rate to finding the pipe size? At this point you must consult your plumbing code and look for an appendix for sizing the water supply system (all the model codes have one). If your adopted plumbing code does not have this appendix, then refer the 2015 *Uniform Plumbing Code*, Appendix A for a good reference guide.

Generally, the sizing rules begin with estimating the demand in fixture units, and then converting fixture units into flow rates (gpm). This step can be eliminated since the Water Demand Calculator predicts the house's demand in gallons per minute. The sizing rules will then lay out steps for calculating friction loss and direct you to nomograph charts that include friction loss, velocity, and flow rate to determine the appropriate pipe size.

Codified provisions and examples for using this calculator will debut in a new appendix in the 2018 *Uniform Plumbing Code* as well as the 2017 WEStand.

The Water Demand Calculator may be downloaded by following the link below. The Excel spreadsheet contains macros that will automatically flag a warning about potential viruses and corruptions when you download the file. Once the file is trusted, the warning will no longer appear.

http://www.iapmo.org/WEStand/Pages/DocumentInformation.aspx

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