FREQUENCY OF PLUMBING FIXTURE USE THROUGH AUDIO SAMPLING

A Senior Honors Thesis

By

KEVIN BRUCE SHEA

Submitted to the Office of Honors Programs
& Academic Scholarships
Texas A&M University
In partial fulfillment of the requirements of the

UNIVERSITY UNDERGRADUATE
RESEARCH FELLOWS

April 2000

Group: Physical Sciences

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April 2000

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ABSTRACT

Frequency of Plumbing Fixture Use

Through Audio Sampling. (April 2000)

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Pipe sizing criteria, and thus building water utility connections, are currently based upon a very small statistical sampling of plumbing fixtures performed in the late 1930's. This sampling became the basis for the Hunter curves. The Hunter curves remain the industry standard and are used to size piping systems based on the number of plumbing fixtures attached to the water supply system. There is general agreement, however, that use of these curves result in inefficient or insufficient water piping supply systems. As a result of the application of the Hunter curves, the water supply configurations are often miss-sized. Incorrect pipe sizing translates into higher material and labor costs during construction. With changes in personal habits, fixture design, and building use, the applicability of these 50-year old curves is questionable.

A preliminary experiment was conducted whereby the WERC building on the Texas A&M University campus was continuously monitored for one week. The experiment involved mounting a microphone on the water supply riser for a bank of water closets.

Data collected was used to estimate maximal usage patterns and probabilities of the concurrent use of multiple water closets. The estimated probabilities were compared to the Hunter Curves. Although based on a very limited sample, the comparisons suggest the Hunter Curves may underestimate maximal usage patterns.

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INTRODUCTION

The primary use of potable water in most institutional/commercial buildings in the United States is through plumbing fixtures. These normally consist of some combination of lavatories, water closets, and urinals. Though efforts have been made to improve the design and operation of these fixtures, very little work has been done regarding frequency of fixture use or use patterns in over 50 years (Swaffield and Gaolwin, 1992). Pipe sizing criteria and thus building water utility connections are based upon a very small statistical sampling of fixtures that was performed in the late 1930's (Hunter, 1940). The sampling became the basis for the curves that bear Hunter's name. The Hunter curves are still used today to size piping systems based on the number of plumbing fixtures attached to the water supply system. There is general agreement that use of these curves results in inefficient or insufficient water piping supply systems. They are largely mis-sized which translates into higher material and labor costs during construction (Williams, 1976).

With changes in personal habits, fixture design, and building use the applicability of these 50-year-old curves is questionable. Updating the Hunter design curve would require sampling the frequency of use of the type of plumbing fixtures found in modern buildings.

This thesis follows the style and format established by the Journal of the American Society of Heating, Refrigeration and Air-Conditioning Engineers.

LITERATURE REVIEW

Prior to 1940 the accepted way to size plumbing systems involved experience factors and rules of thumb. The design methodology employed today in configuring the supply systems does not allow for the consideration of all the fixtures in simultaneous operation. The simplistic task of summing all of the fixtures discharging would lead to a system being oversized and to increased maintenance (Swaffield and Gaolwin, 1992). The design approach has a much more in depth analysis. The method normally employed introduces basic statistical methods to configure usage patterns and probabilities. Consider a fixture that has a cycle of t in seconds and a usage pattern of T in seconds. The probability of finding that fixture in use is give, by the equation

$$\theta = t / T \quad (1)$$

The probability of finding the fixture not in use is given by the equation

$$Q = 1 - \theta \quad (2)$$

When two or more fixtures exist the probability of finding one or the other in use is given by $P = P1 + P2$ where P1 and P2 are the individual usage probabilities. When both fixtures are to be found in use at the same time the equation $P = P1 * P2$ is used. For X fixtures to have the same individual probability of use the equation $P = P1^X$ is used.

For example if a urinal has a discharge cycle of 7 seconds and is used every 350 seconds, then the probability of finding the fixture in use is

$$P = 7 / 350 = 0.02 \quad (3)$$

If 6 urinals are employed the probability of finding all 6 in use at the same time is

$$P = (0.02)^{6} = 6.4 \times 10^{-11} \quad (4)$$

The probability of finding none of the fixtures in use is

$$Q = (1 - 0.02) = 0.98^{6} = 0.8858 \quad (5)$$

This shows that 88.6 % of the time none of the 6 urinals are being used. This is why the design method of simultaneous usage is not acceptable. The prediction of simultaneous usage from any number of urinals 0 to 6 is calculated by a binomial distribution (Swaffield and Gaolwin, 1992) where

$$P = C_r^n (1-p)^{n-r} \text{ where } C_r^n = {}^{n!}/_{r!(n-r)!} \quad (6)$$

The design norm that has been selected and used is a probability value of 0.01 which implies that the actual load imposed should only exceed the design load for less than 1% of the time. This design norm was established and accepted by the original work of Roy B. Hunter. Roy B. Hunter performed the first systematic statistical study on water and supply drainage in 1924. Hunter addressed the problem that different fixture types pose on a water supply system. Hunter developed the "fixture unit" as a way of weighting the various types of plumbing fixtures. A "fixture unit" is a numerical value that measures, on an arbitrarily chosen scale, the load effect of a single plumbing fixture of a given type (Hunter, 1941). The application of fixture units allows the user to reduce the load producing characteristics of different fixture types to a common basis (Hunter, 1940). Hunter developed the fixture unit originally on a scale of 1 to 6 (Hunter, 1924). Later in 1940, Hunter suggested that a decimal scale of 1 to 10 should be used (see Table 1).

Table 1
Water supply fixture unit values with corresponding occupancies (Nielsen, 1982)

Fixture	Occupancy	Type of Supply	Supply Fixture Units Cold	Hot	Total
Water Closet	Public	Flush valve	10		10
Water Closet	Public	Flush tank	5		5
Urinal	Public	1" flush valve	10		10
Urinal	Public	3/4" flush valve	5		5
Urinal	Public	Flush tank	3		3
Lavatory	Public	Faucet	1.5	1.5	2
Bathtub	Public	Faucet	3	3	4
Showerhead	Public	Mixing valve	3	3	4
Service sink	Offices, ect.	Faucet	2.25	2.25	3
Kitchen sink	Hotel, resturant	Faucet	3	3	4
Drinking fountian	Offices, ect.	3/8" valve	0.25		0.25
Water Closet	Private	Flush valve	6		6
Water Closet	Private	Flush tank	3		3
Lavatory	Private	Faucet	0.75	0.75	1
Bathtub	Private	Faucet	1.5	1.5	2
Shower stall	Private	Mixing valve	1.5	1.5	2
Kitchen sink	Private	Faucet	1.5	1.5	2
Laundry trays (1 to 3)	Private	Faucet	2.25	2.25	3
Combination fixtures	Private	Faucet	2.25	2.25	3
Dishwashing machine	Private	Automatic		1	1
Laundry machine 8lb	Private	Automatic	1.5	1.5	2
Laundry machine 8lb	Public or general	Automatic	2.25	2.25	3
Laundry machine 16lb	Public or general	Automatic	3	3	4

The limits on the fixture unit scale were set as the largest load being the water closet and the smallest load being the lavatory (Hunter, 1940). Hunter developed these relative fixture units from the probability functions discussed earlier. The part of the probability function that requires the usage pattern in seconds came from Hunter's observation of hotel and apartment wake up calls (see Table 2).

Table 2
Example of the data from hotel wake up calls (Hunter 1940)

	Time of call am									
Place	Before 6:30	6:30	6:45	7:00	7:15	7:30	7:45	8:00	After 8:00	Total calls
Hotel 1	174	228	98	486	146	700	185	463	382	2862
Hotel2	198	212	133	599	176	780	176	722	341	3057
Total calls	372	440	231	1085	322	1780	361	905	723	5919

Hunter assumed that at the time of rising the bathroom group would be used. The bathroom group normally consisted of a water closet, a lavatory, and a bathtub or a water closet, a lavatory, and a shower stall. The data that Hunter collected from the wake up calls allowed Hunter to assumed an average of 300 seconds between fixture usage. Hunter also based all of his calculations on a flush valve having a 9 second operation cycle and a demand flow of 27 gallons per minute. These values were then used to obtain the probability factor of 0.01. The observations made by Hunter allowed him to, assign different fixture unit values to various plumbing fixtures depending on the occupancy of the building and second, develop the Hunter diversity curves. The two classes of fixture units that he developed were private and public, with public having the greater fixture unit values because of the increased usage (see Table 1). When estimating the demand load for a supply pipe in any building using Hunter's fixture unit method, the total number of different fixture types should first be summed to a total number. That total number is then multiplied by the appropriate fixture unit value for each individual fixture type. All of the fixture units are summed for a total number of fixture units. The total number of fixture units are then found on the Hunter curves, (Figure 1), where the corresponding flow rate, in gallons per minute, are found (Hunter, 1941). The flow rate is then used with standard pipe sizing charts to determine the appropriate pipe size. These pipe-sizing charts take into account velocity, flow rate and service conditions. The result of Hunter's work and the development of the Hunter curves indicated design demand loads of 20 up to 40 percent lower that would have been predicted by other design methodologies of the time.

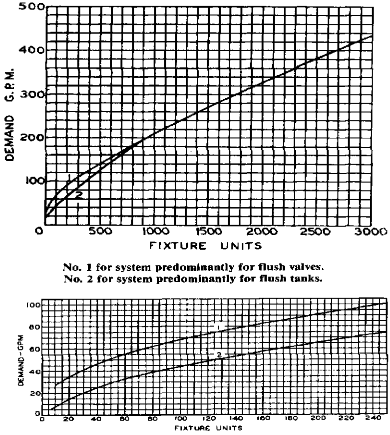

Figure 1. The Hunter diversity Curves (Hunter, 1940)

In 1976 Gerald Williams presented his work on revising the Hunter Diversity curves (Williams, 1976). Williams hypothesized that Hunter's estimate of a 300 second interval between fixture usage developed from hotel and apartment wake up calls was not always correct. Fixture use for hospitals, schools, restaurants, sports stadiums, and offices could have very different usage patterns. Williams pointed put that some of the essential statistics that Hunter used were no longer valid. Flush valve operation had fallen from 9 seconds to between 6 and 7.5 seconds. Flow rates had increased from around 27 gallons per minute to between 31 and 35 gallons per minute. All of these parameters needed to be updated. Williams conducted several experiments at sports stadiums and athletic events to monitor fixture usage. Williams limited his experiments to monitoring flush valve water closets that had a 7.5 second flush duration and a flow rate of 31.5 gallons per minute. When Williams compiled his data he determined that the frequency of usage was every 40 seconds for men's and 60 seconds for women's water closets. Also, he noted that the test participants sometimes reacted with abusive or even downright unfriendly behavior because they were being monitored. Williams averaged his data to arrive at an average T of 50 seconds. When this average of 50 seconds was used in equation one, the probability was found to be $\theta = 0.015$, compared to Hunter's probability of $\theta = 0.03$. Williams then proceeded to use the binomial probability distribution as described earlier. The distribution allowed him to determine the number of fixtures *m* out of the *n* total number of fixtures that would produce an acceptable design. Williams plotted his curve of gallons per minute verses fixture units as Hunter had done in 1940 (see Figure 2).

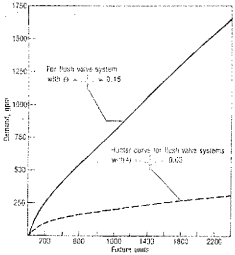

Figure 2. Williams curve against the Hunter Curve
(Williams, 1976)

Williams used the new 31.5 gallons per minute times the *m* number of fixture units that would produce an acceptable design to establish his curve. When the two different curves are compared three main points emerge. One, the original design using Hunter's curves calls for a design load of 215 gallons per minute. Second, William's revised curve calls for a design load of 800 gallons per minute, and third, the additional demand for all of the fixtures is 3150 gallons per minute. Williams concluded that Hunter's work was sound but that it could not be applied to a wide range of building classifications. Williams stated that for the purposes of his experiment strict adherence to the Hunter curves would lead to a considerable under sizing of the water supply system. Williams's final conclusion was that a variety of diversity curves should be developed to cover different building classifications (Williams, 1976).

In the early 1990's a small-scale study of plumbing fixture usage in the United Kingdom was performed (Butler, 1991). Butler collected data by means of a survey, which consisted of three parts: a questionnaire, a diary, and the testing of individual appliances. The questionnaire asked about background information, such as dwelling type and age. The questionnaire also asked about the number of occupants, age, occupation, and appliance ownership. The participants recorded every time a fixture was used and the mode of use such as a sink running to waste or running to drain. The final part of the experiment required the participant to perform experiments on their fixtures to determine the duration of operation. 28 households with a total of 76 people completed the diary sheets. Butler compiled his data and had hourly and daily patterns of usage. Butler had problems comparing his data with published data of the time but he made some progress with the water closet noting that usage was consistent throughout the week. Butler concluded that most fixtures showed clear morning peaks followed by smaller evening peaks. Butler also noted that his small-scale study provided useful information but further information, data collection, and research needed to be conducted (Butler, 1991). Another study suggested that each type of building should be analyzed independent of the other (Heideman, 1999). The first building category was airport terminals. He advised that the plumbing engineer should work closely with the architect to determine the occupancy loads. Once the loads are determined, the engineer should calculate flow rates using at least two separate water services to the terminal. The next building category was stadiums and arenas. Heideman suggested that the engineer should determine the usage of the building such as single sport or multipurpose sport.

The multipurpose venues provide a challenge for both the determination of the number of fixtures and the determination of the male to female ratio. Convention centers that accommodate large groups are the simplest to design while cinemas and theaters have unique design requirements. Heideman concluded with the comparison of three plumbing codes: the International Plumbing Code (IPC), the Southern Building Code Congress International (SPC), and the Uniform Plumbing Code (UPC). He pointed out that the plumbing engineer needed to pay close attention the local and state codes because many have enacted laws modifying the codes. All of the codes use, in some form of another, the Hunter curve methodology so careful attention should be placed on the sizing of the water distribution systems (Heideman, 1999).

EXPERIMENTAL PROCEDURE

Using an in-situ method to collect plumbing fixture use data would be difficult to implement. As described in the literature review, Williams found that users could become hostile in that situation. There are flow meters and sensors available that could be used for this work however, there are several disadvantages of physical metering. The costs for meter installation and data-logging would be significant and the installation would be difficult and invasive. Ultrasonic flow metering techniques are well known and established, but these methods are not well suited to conduct the type of sampling needed (Holman, 1984). Evaluating the work of Williams with the obvious social obstacles it became apparent that the method of data collection needed to be non-intrusive.

Most water supply pipes conduct some noise when used. This led to the idea of monitoring fixture usage by acoustic means. Using sound conducted through the water supply piping system seemed to offer a simple, noninvasive, and inexpensive method to capture plumbing fixture use data. Microphones and attachment methods were developed to monitor supply pipe noise as a surrogate for fixture use. A microphone attachment was designed to be attached to the water supply piping risers of the three different fixture groups that were to be monitored. A total of three different microphone-mounting methods were developed. A direct mount using a modified PVC "T" fitting, a sheet-metal spring clip with an attached stethoscope, and a modified electrical switch box with an internal stethoscope that could be clamped to a pipe. The third floor men's restroom of the Langford Architecture building "A" at Texas A&M

University was chosen for the first test. The women's restrooms were initially excluded until the acoustic system could be fully developed and proven in use. Microphone attachments were mounted to the three supply risers at the 3rd floor men's restroom: the water closet riser, the lavatory riser, and the urinal riser. Standard four pair, 22 ga. telephone wire was connected to the microphones and terminated at an office adjacent to the restroom.

A logical extension for the sound based system was to terminate the microphone at the sound card of a personal computer. Modern PC sound cards are capable of very sophisticated sound capture which allows for subsequent analysis. The microphone signals from the risers were connected to a four channel audio mixer where they could be mixed and amplified. The mixer was necessary because PC soundcards typically have only one microphone input.

To avoid the need for custom sound analysis development and custom programming, the use of voice recognition software was explored. Current voice recognition software is commonly used in lieu of keyboard input for typing text into a computer. The voice recognition software used a standard PC soundcard as input and initial experiments on single fixtures were encouraging. This led to the idea of using voice recognition as a means of data collection since the system seemed to recognize and distinguish different noises such as a door closing or a water faucet being used. The software was further tested using audio wave analysis software. The first part of the testing involved training the software which had to distinguish the three different fixture groups and identify each type of fixture. The software was successful at first because most of the training was performed at night. A short macro program was written to link the voice recognition software with Microsoft Word. The macro monitored the soundcard input and upon a fixture usage it would record the fixture type, time, and date into a Word table. Preliminary experiments showed that the software could detect fixtures on all four floors of the Langford Architecture "A" building. This posed a problem because during the day the voice recognition software had problems with extraneous noises. It became evident that the software was having problems with cross talk between floors which would cause false data records to be detected. Evidently, the noise levels in the building varied enough that it became impossible to maintain consistent sound recognition training. In light of the noise problems, all four men's restrooms were individually wired in hopes of eliminating or reducing the extraneous noise and cross talk. Each floor needed an individual computer so four Pentium PC based sound monitoring systems were built. The noise problem became an obstacle because the software still had difficulty with cross talk, which led to unreliable data collection.

Another approach was developed using a PC based data acquisition system. The new method eliminated the software and used a standard data collection board for input from the microphones. Initial testing with this method was conducted to determine if the data collection boards could recognize the signal from the microphones. These tests showed that the microphones needed to be amplified for proper detection. This system was installed in the basement men's restroom of the Weisenbacker Engineering Research Center (WERC) building on the Texas A&M University campus. Microphones were attached to the three main fixture risers (water closets, urinals, and lavatories) and wire was installed back to an adjacent office. Unfortunately, the system was never operable because of amplification problems. It seems that the length of the wiring runs caused excessive signal degradation. The system was abandoned in search of a new data collection method.

Because of the difficulties with the first system types, a more basic approach was taken for the next device. A simple circuit was built that activated a relay when subjected to a loud noise. The circuit still relied on a microphone attached to a pipe for the noise source, but the "back-end" of the circuit did not need the sophistication of the previous data acquisition methods. The form-A relay output was connected to a digital only data-logger that recorded the relay closures. A potentiometer in the circuit allowed for sensitivity adjustment of the microphone. The data logger recorded the total number of relay closures that occurred for each successive five minute interval. This gave the total number of flushes occurring in a five-minute interval. The first circuit developed was attached to the water closet supply riser. This pipe supplied four water closets in the men's restroom and three water closets in the women's restroom.

Data collection using the previous methods was limited because of technological limitations, instrumentation issues, and inconsistent software behavior. However, the data that was collected with the new system has shown to be consistent and repeatable. Some statistical analysis and discussion of the limited data collected thus far is presented in the next chapter.

RESULTS AND DISCUSSION

Data was collected on seven water closets for a period of one week. The frequency of usage is presented for each day at 5-minute intervals in Figure 3. As can be seen from the plots and associated polynomial regression lines, the frequency of use per 5 minute interval was quite stable from Monday through Thursday (mean = 1.61, standard deviation = 1.92). A unique profile was found for Friday (mean = 1.86, standard deviation = 2.07) and the weekend (Saturday and Sunday: mean = 0.95, standard deviation = 1.39). In addition, the peak usage for the 5-minute collection periods was also extremely stable from Monday through Thursday. However, two estimates have been taken; one liberal (mean = 13.0, standard deviation = 0.70) and one more conservation (mean = 8.6, standard deviation = 1.67) estimate. Liberal and conservative estimates of peak flow are shown in Figure 4. The liberal estimate of peak flow was defined as the 5-minute interval with the highest usage in a 24-hour period. However, because this interval may have included additional usage related to janitorial services, a more conservative estimate was also determined. The conservative peak usage estimate was defined as the second highest usage period.

The measures of peak usage are especially important because these are the values that are used to compare to the Hunter curves and used in the determination of the peak flow probability curves. As a result of the preliminary analyses, the peak flow values from Monday through Thursday were used as estimates of peak flow in further analyses.

Using the procedures first developed by Hunter, the probability of a particular fixture use is given by

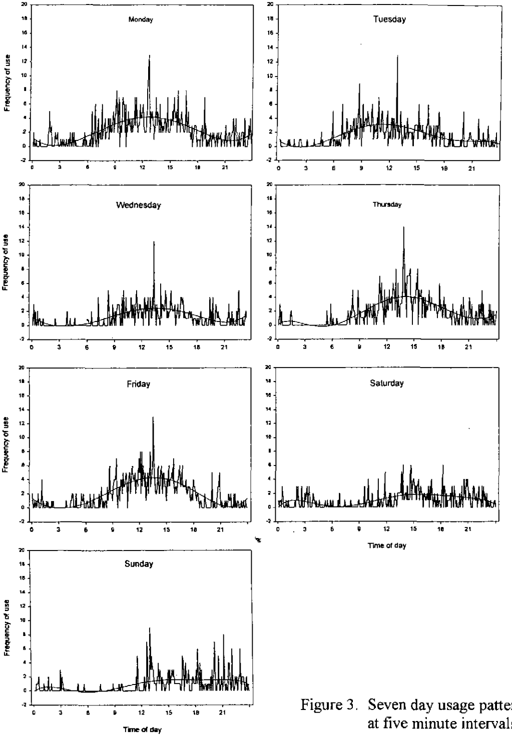

Figure 3. Seven day usage patterns at five minute intervals

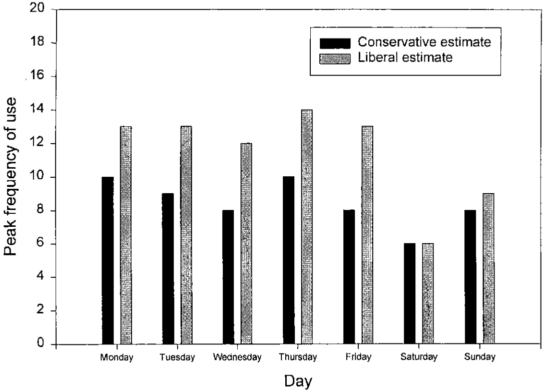

Figure 4. Liberal versus conservative peak flow rates

$$\theta = t/\mathrm{T} \tag{7}$$

where t is the duration of the flushvalve action and T is the average time between flushevalve use. Using the liberal estimates, the duration of the valve action for the water closet test was 5.5 seconds and the average time between valve use was 23 seconds. This yields $\theta = 0.239$. Clearly this level of probability is not realistic considering that the average time interval at maximum congestion for males and females to use the water closet was approximately 50 seconds (Williams, 1976). Using the conservative estimates of an average time between fixture use of 50 seconds, $\theta = 0.11$. These values can be compared to $\theta = 0.03$ found by Hunter who estimated the probability of usage in hotels by monitoring wake-up calls and, $\theta = 0.15$ found by Williams who monitored usage during periods of maximum congestion during large sporting events. Thus, the conservative estimates suggest that fixture usage in this particular restroom group is similar to that seen in large venues such as stadiums and theatres. The probabilities of water requirements for one through four water closets being activated at the same time are given in Table 3. Hunter's work resulted in a commonly accepted standard that requires meeting fixture demand 99% of the time. From the data estimated in Table 3 for four water closets, a minimum water supply capacity of greater than approximately 63 gallons per minute would be required. In the bathroom group tested, a 2.0 inch diameter pipe supplied the water closets. This supply pipe, provided it operated at a pressure greater than 25 psi, should be more than adequate to meet peak demand.

Table 3
Percent of occurrence related to number flushes

Gallons Per Minute	Percent of occurrence	Number of simultaneous flushes
31.5	11%	1
63	1.21%	2
94.5	0.013%	3
126	$.001^{-4}$%	4

CONCLUSIONS

The present study monitored water closet usage for the male and female restrooms in the basement of the WERC for a period of one week. Stable usage patterns were found for Monday through Thursday with lower usage patterns for Friday through Sunday. These usage patterns may be unique to this academic building. The results of the limited data collection suggests that maximal usage occurs during the middle of a weekday period. The results of the preliminary analyses indicated that peak water demand was greater than about 63 gallons per minute. This water demand occurs only when two water closets were used simultaneously. According to the present data this should occur only 1.3 % of the time (see Table 3).

Based on the present study the following conclusions seem warranted.

- Water usage was highest (1.5 fixture uses/minute) through the middle of the day Monday through Thursday and this pattern was repeated for each weekday.
- The Hunter curves appear to underestimate peak water demand when fixture use is based on an average (0.30 flushvalve uses per minute) for this study. Peak water demand (1.4 uses per minute) was more in line with the findings of Williams (1976).

Recommendations

Further study of this topic should consider the following:

- A larger number of water closets should be monitored over longer periods of time.
- Data should be collected at diverse building locations to allow sampling of different populations and usage patterns.
- The data acquisition system should be capable of distinguishing usage of sinks, water closets, and urinals.
- The temporal attributes of water usage per event should be determined.
- Determine the relationship between building occupancy and plumbing fixture use.
- The actual capacity of the supply line (diameter, service pressure, and resistance) should be determined.
- Distinguish between normal and unusual (custodial cleaning crew) usage.

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