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The Impact of Building Occupancy on Water Demand Characteristics in Residential Buildings: A Sensitivity Analysis †

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Abstract: A stochastic water demand model was used to undertake a sensitivity study to evaluate building occupancy against selected premise plumbing design parameters. The results demonstrate that building occupancy has a strong positive correlation for estimating the peak demand, average demand, and peak hourly water consumption (Spearman's coefficient: 0.995–0.99), and a strong negative correlation to stagnation (the percentage of time a building spends at zero flow; Spearman's coefficient: −0.996). The results indicate that building occupancy should be taken into consideration in premise plumbing design, which currently mainly focuses on the type and number of fixtures.

Keywords: plumbing design; premise plumbing; pipe sizing; residential buildings; water demand

1. Introduction

Research has developed practical tools to address the over-estimation of peak demand for the design of premise plumbing systems [1,2]. Examples of these modern approaches include the Water Demand Calculator offered by the International Association of Plumbing and Mechanical Officials (IAMPO) in the US [3], and the cold-water 99th-percentile demand calculator offered by the Hydraulic Consultant Association of Australasia (HCAA) [4]. These new tools break away from the conventional 'fixture units' approach developed by Roy. B Hunter in the 1940s [5]. This is achieved through the incorporation of water end-use data from residential households to determine the 'probability of use' values for specific fixtures during the peak hour of water consumption. Probability values are integrated into design formulas to estimate the 99th-percentile demand flowrate (peak demand) required to select appropriate pipe sizes.

New tools have provisions built into their formula for considering building occupancy. Still, design formulas are fundamentally concerned with the type and quantity of fixtures that feature in a specific plumbing network, lacking any major consideration of occupancy. Another shortfall is that they only estimate the peak demand, which is a limited design metric when attempting to size plants, water storage facilities, and control valves in plumbing networks. This is because plumbing systems rarely reach peak conditions, and they spend the majority of their time in zero- or low-flow scenarios [6]. The water consumption across the entire day needs to be known in order to prevent oversizing and improve system performance in terms of energy consumption, embodied carbon, and water quality aspects.

It is expected that water consumption patterns are influenced by building occupancy. In order to better understand the water consumption characteristics of residential buildings, the current study conducts a sensitivity analysis to consider the influence of occupancy on (1) the peak demand, (2) the average demand, (3) water consumption during the hour of greatest water use for each day, defined as the 'average peak hour water consumption', and (4) stagnation (the amount of time spent at zero flow) in residential buildings. Finding offer

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an improved understanding of all four design parameters can assist hydraulic practitioners to make better selections when choosing premise plumbing components.

2. Materials and Methods

2.1. Study Design

This sensitivity analysis assumed a fixed apartment design with respect to plumbing fixtures, which included 2 × showers, 4 × taps, 1 × washing machine, 1 × dishwasher, and 2 × toilets. Bath use was excluded from the analysis due to the low use of baths in Australia.

In total, 100 days of water consumption was simulated for various building sizes (buildings with various numbers of apartments). Simulations were run to incrementally increase the building occupancy from 1 to 300 building occupants. A total of five simulations were run with a fixed apartment occupancy of 1, 2, 3, 4, and 5 occupants, respectively. Results for each plumbing parameter (y-axis) were plotted as a function of the occupancy (x-axis). To determine occupancy's influence towards water consumption, Spearman's rank correlation coefficient [6] considering data from all five simulations was calculated for each plumbing design parameter. Non-linear functions were fitted to the simulated datasets and are presented herein.

For the current study, the 'peak demand' is defined as the 99th-percentile flowrate for all non-zero flowrates observed for all simulated days of water use during the peak hour of water consumption. The 'average demand' is defined as the arithmetic mean for all non-zero flowrates observed during all periods of simulated water use. The 'average peak hour water consumption' is defined as the arithmetic mean for each maximum hourly water consumption across all 100 days of simulated water use. 'Stagnation' is defined as the percentage of time a specific building's plumbing system is stagnant (at zero flow) considering all 100 days of simulated water use.

2.2. Stochastic Water Demand Model

To execute this sensitivity analysis, water consumption was simulated considering the total water demand (hot + cold) in residential apartment buildings using a stochastic water demand model developed based on Australian residential fixture usage characteristics [2]. Equation (1) defines the simultaneous flowrate (summations of all fixture demand pulses) for each second of the daily water consumption. For each day, the model evaluates a specific residential building with a predefined number of apartments. Within each apartment, a specified number of occupants ranging from 1 to 5 is considered. For each household occupant, the frequency of use (F) for each apartment fixture is established. For every fixture event, the demand pulse (P) [Equation (2)] is a function of the intensity (I), duration (D), and time of use (τ). The demand pulse is equal to the intensity when $\tau < t < \tau + D$, and is zero elsewhere. Model parameters F, I, D, and τ are all described by empirical probability density functions (PDFs) gleaned from five Australian residential end-use studies.

$$q(t) = \sum_{r=1}^{B} \sum_{m=1}^{U} \sum_{j=1}^{W} \sum_{i=1}^{F_{jmr}} P(I_i, D_i, \tau_i) \tag{1}$$

$$P(I_i, D_i, \tau_i) = \begin{cases} I_i & \tau_i < t < \tau_i + D_i \\ 0 & elsewhere \end{cases} \tag{2}$$

3. Results

Presented in Figure 1 are the simulated water consumption results for the four premise plumbing design parameters. Each parameter is plotted as a function of building occupancy considering five different occupancy scenarios, ranging from one to five people per building apartment. Each apartment had a fixed number of premise plumbing fixtures. Presented in each plot are the Spearman correlation coefficients. A value of 1 depicts an exact positive correlation (y increases with x), a value of −1 depicts an exact negative correlation (y decreases as x increases), and a value of 0 represents a weak correlation.

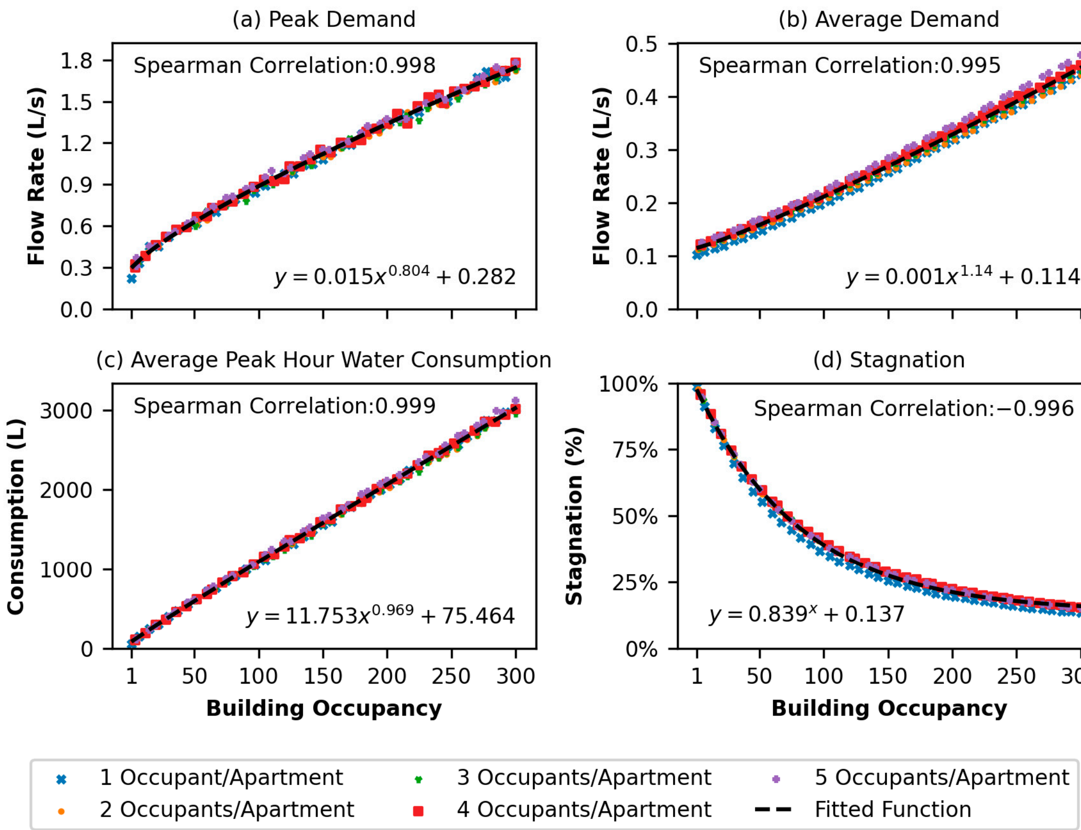

Figure 1. Simulated water consumption results considering four plumbing design parameters—(**a**) peak demand, (**b**) average demand, (**c**) peak hour water consumption, and (**d**) stagnation—as a function of building occupancy for five simulated water consumption scenarios that assume fixed apartment occupancy levels ranging from 1 to 5 people.

The peak demand (99th-percentile flowrate) presents a strong positive relationship, with a Spearman coefficient value of 0.998. The fitted function relationship is non-linear, and the impact each occupant has on the peak demand diminishes as the building occupancy increases.

The average demand presents a strong positive relationship, with a Spearman coefficient value of 0.995. The fitted function is non-linear. Interestingly, the impact each occupant has on the average demand varies from the behavior of the peak demand, increasing slightly with the building occupancy.

The average peak hourly water consumption is seen to have a positive relationship, with a Spearman coefficient of 0.999. Considering the almost linear nature of the fitted function, for the conditions simulated, each additional occupant, greater than one person, adds approximately 10 L to the peak hour consumption.

The stagnation exponentially decreases with an increase in building occupancy. For the simulated conditions, stagnation as a function of building occupancy presents a strong negative correlation, with a Spearman coefficient of −0.996.

4. Discussion

The results demonstrate that residential water consumption characteristics are highly sensitive to the total building occupancy, but not to the average number of occupancies per apartment. This offers building occupancy as an important factor to consider for several plumbing design parameters. In addition, the ability to estimate design values in addition to the peak demand presents hydraulic designers with an opportunity to better select plumbing plants and equipment.

The results also highlight that current design practices that only consider the total number of fixtures may be limited in accurately estimating the peak demand. The results support this research team's previous work [2] in which fixture probability was adjusted according to both building size (the number of apartments) and building occupancy.

5. Conclusions

A sensitivity study considering the impact of building occupancy toward four premise plumbing design parameters was undertaken. Using a stochastic water demand model, a fixed apartment design with respect to plumbing fixtures was used to simulate water consumption for buildings with varying sizes (numbers of apartments) and levels of apartment occupancy. The results demonstrated that building occupancy has a strong positive correlation for estimating the peak demand, average demand, and average peak hour water consumption (Spearman's coefficient: 0.995–0.99), and a strong negative correlation to stagnation (i.e., the percentage of time a building spends at zero flow; Spearman's coefficient: −0.996). The results also demonstrate that beyond the type and number of fixtures, building occupancy is also an important parameter supporting the estimation of key premise plumbing design parameters.

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