Identifying Limitations of Australian Standards for Cold-water Plumbing Design: Comparing Actual and Designed Demand in Multi-level Residential Buildings

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Brendan Josey
Civil Engineering Graduate
Email: bjosey@deakin.edu.au

Dr James Gong
Lecturer in Water Engineering
Email: james.gong@deakin.edu.au

School of Engineering

Faculty of Science, Engineering and Built Environment

Deakin University

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EXECUTIVE SUMMARY

This research is the first systematic study on the actual water demand in Australian multi-level residential buildings. Research conducted throughout this report consists of three components to identify the current limitations of Australian cold-water service design standards and practices. The separate bodies of work include:

1) Literature review of methodologies used to estimate peak hydraulic demand in plumbing systems;
2) Analysis of the actual water consumption within four specific Australian multi-level residential buildings; and
3) A case study of the steady-state hydraulic condition in a specific multi-level residential building through single- and extended-period numerical modelling.

The research has provided scientific evidence that the actual state of a building's hydraulic condition and performance can be very different from the expected conditions as designed from current standard AS/NZS 3500.1. Key limitations identified in current plumbing design standards and practices include:

1) Over-estimation of peak hydraulic demand;
2) Oversizing of pipes, pumps, and plumbing hardware; and
3) Inadequate consideration to varied states of flow such as low-demand periods and unsteady flow conditions (water hammer).

The most considerable limitation is the over-estimation of the peak hydraulic demand. Results demonstrate the current Australian plumbing standards significantly overestimate peak flow rates by a range of 217-326% for the four Australian multi-level residential buildings studied. Peak demand is a key parameter in determining a plumbing system's final design configuration under the current design standard AS/NZS 3500.1. Over-estimation of the peak demand results in oversizing of the overall plumbing system, which then costs more money for construction and operation, and increases the risk of plumbing defects.

A downsized plumbing system (the "re-sized scenario") has been considered in the numerical case study to explore the impact of reduced pipe and pump sizes. The largest pipe size can be reduced from DN100mm to DN40mm whilst still maintaining compliant operating conditions set within the Australian plumbing standard AS/NZS 3500.1. While the results have demonstrated significant potential of downsizing, they should not be considered as a simple solution to the limitations identified. Many complexities, such as hydraulic transients and trapped air, have not been considered in the current research.

The findings in this research indicate that there are major opportunities for the industry to provide the public a more sound and efficient plumbing design that will ultimately improve longevity and reduce lifecycle costs associated to both hot and cold-water systems. Moving forward, efforts should be focussed on developing new standards to more accurately estimate peak hydraulic demands and optimally size the pipes, pumps and other flow control devices. Future development should also consider whole plumbing system performance under various states of flows (in addition to the peak flow) to ensure system performance is not comprised through updated design practices. Four research and development topics are recommended, and they are:

1) Water demand and pressure monitoring for various types of buildings in Australia;
2) Extended-period hydraulic modelling;
3) Hydraulic transient analysis; and
4) Reviewing existing issues related to premise water services in Australia.

INTRODUCTION

The peak flow rate (peak demand) is a critical parameter in plumbing network design. This value determines the size of pipes, booster pumping systems, plumbing hardware, and appurtenances. Typically, this value is estimated through methodology set within international plumbing codes. However, there is now substantial evidence that many international plumbing codes significantly over-estimate the peak demand value because of the advent of water efficient fixtures and appliances (Bleys et al., 2012, Tindall and Pendle, 2015, Jack et al., 2017, Douglas et al., 2019). This over-estimation can lead to over-sized plumbing systems that operate outside the intended hydraulic conditions, resulting in increased construction costs, reduced water quality, elevated energy consumption, and increased risk of premature failure of plumbing hardware.

Based on the conclusive international evidence that international plumbing codes over-estimate peak hydraulic demand, the Hydraulics Consultants Associations of Australasia (HCAA) have undertaken high-resolution monitoring of four multi-level residential building located in Australian capital cities. The project's goal is to compare flow rate data against the current Australian plumbing standard AS/NZS 3500.1 Plumbing and Drainage Part 1: Water Services (AS/NZS 3500.1:2018) to ascertain if over-estimation is prevalent within the Australian plumbing industry.

In addition to the water demand investigation project setup by the HCAA, the Australian Building Codes Board (ABCB) is currently investigating the impacts of changes to methodology that hydraulic practitioners will use to estimate the peak flow rates. A methodology under review, nominated as the Verification Method (VM) is based on an algorithm developed by Wistort (1994). Case studies commissioned by the ABCB and undertaken by Lucid Consulting Australia (2019) have already demonstrated a reduction in the estimates peak flow rates of multi-level residential buildings when compared to the current Australian plumbing standard.

To establish whether significant over-estimation of peak flow rates exists within Australian buildings, the current research compares high-resolution flow rate data obtained from the HCAA's water demand investigation against the current Australian plumbing standard, the ABCB's verification method and comparable international plumbing codes. All nominated methods reviewed are used to predict a specific building's 99th percentile design flow rate.

Furthermore, many international studies have considered only a plumbing standard's ability to estimate peak flow rates. Much of the standing research fails to consider the impacts a reduction in pipe, pump and control devices size may have towards a plumbing system's operation. To assess both current and future states of water service design, a case study of a nominated building used within the HCAA's water demand investigation is conducted through numerical hydraulic modelling. The modelling aims to develop a more detailed understanding of the hydraulic conditions experienced within multi-level residential buildings, through the evaluation of two system design scenarios evaluated over single and extended time periods. The nominated system designs are 1) AS/NZS 3500.1 (as built) and 2) re-sized (future state). The AS/NZS 3500.1 scenario reflects the selected building's plumbing network as per relevant building design documentation. The 're-sized' uses design and industry velocity limits combined with simulated peak flow rates to reduce plumbing componentry size within the respective building's plumbing network. Results from the two scenarios are compared for the adequacy of flow velocity, pressure, head loss and operational efficiency, with consideration of design constraints set with AS/NZS 3500.1:2018 and industry design practices.

LITERATURE REVIEW

Terminology

The report will adopt the terminology listed within AS/NZS 3500.0 to differentiate the fixture loads applied between a cold-water service and a sanitary and drainage service:

- Loading units – fixture loads applied to a heated or cold water service
- Fixture units – fixture loads applied to a sanitary drainage or sanitary plumbing service

Where conflict arises, the term quoted by the original author will be used, followed by a bracketed definition.

Estimating Peak Flow Rates in Residential Buildings

For many international plumbing codes, the foundational methodology is built upon the work conducted by Dr. Roy B Hunter (Hunter, 1940). Hunter recognised that fixture usage followed a binomial distribution in the sense that a fixture was either in use (on) or waiting to be used (idle). Hunter monitored the fixture usage of two hotel buildings during congested usage periods. Recording a specific fixture's time of use (t) and the time between additional use (T), results were used to determine the probability of use (p). With the intent of balancing performance and cost, Hunter used engineering judgement (Jack et al., 2017) that allowed a 1% chance of system overload. Overload does not imply system failure, but rather that the plumbing system may be subjected to flow rates more than the nominated design value. The resultant probability of specific fixture's usage (p), known flow rate (q) and fixture count (n) were used to determine the '99th percentile flow' that is now Hunter's design chart shown in Figure 1.

Recognising that for each specific fixture, the flow rate and probability of use during congested periods varied, Hunter (1940) implemented a system that weighted each fixture relative to the expected load of flush tank toilet, flush valve toilets and bathtubs. This weighted system, termed as 'fixture units' ('loading units' as per AS/NZS 3500.0) (see Table 1) was adopted internationally where modified versions exists in many international plumbing codes (AWWA, 2014).

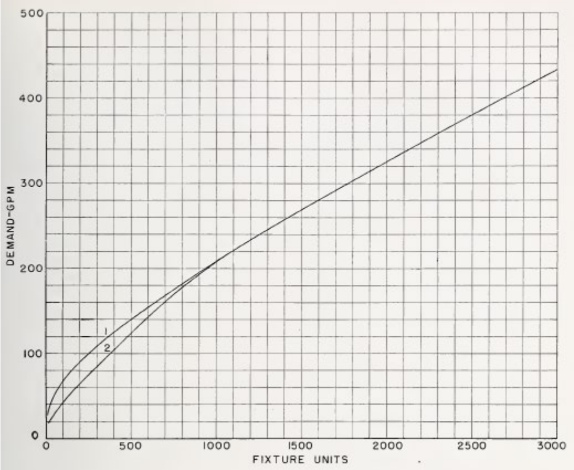
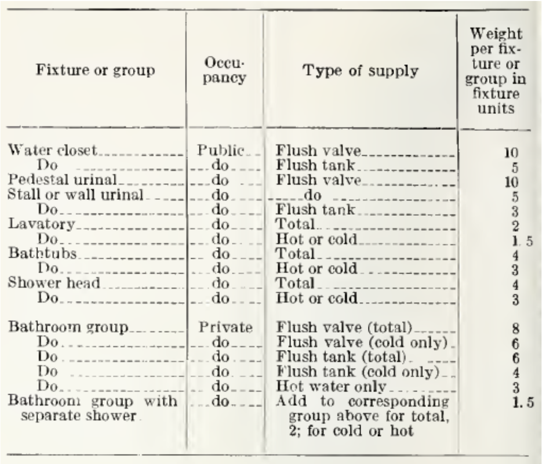


Figure 1 – Hunter design curve (Hunter, 1940)

Table 1 – Design fixture units (loading units) (Hunter, 1940)



Fixture or group	Occupancy	Type of supply	Weight per fixture or group in fixture units
Water closet	Public	Flush valve	10
Do	do	Flush tank	5
Pedestal urinal	do	Flush valve	10
Stall or wall urinal	do	do	5
Do	do	Flush tank	3
Lavatory	do	Total	2
Do	do	Hot or cold	1.5
Bathtubs	do	Total	4
Do	do	Hot or cold	3
Shower head	do	Total	4
Do	do	Hot or cold	3
Bathroom group	Private	Flush valve (total)	8
Do	do	Flush valve (cold only)	6
Do	do	Flush tank (total)	6
Do	do	Flush tank (cold only)	4
Do	do	Hot water only	3
Bathroom group with separate shower	do	Add to corresponding group above for total, 2; for cold or hot	1.5

Over many decades, updates to plumbing technology has led to an increased adoption of water efficient fixtures and appliances. Because of this, plumbing systems now consume less water on a daily basis as well as a reduction to peak flow rates experienced in buildings (Hobbs et al., 2019). To offset this known over-estimation of peak flow rates, many international plumbing codes have altered plumbing design curves, fixture probabilities or loading units. However, these revisions are based on engineering judgement and lack supporting evidence regard their suitability towards premise plumbing design (AWWA, 2014, Omaghomi et al., 2020).

Modern day techniques to estimate peak flow rates can be separated into three categories, 1) probabilistic, 2) empirical and 3) stochastic. Probabilistic and empirical models are most commonly adopted by international plumbing codes (Jack et al., 2017). Probabilistic models are aligned to the work conducted by Hunter, that as mentioned previously, have undergone revisions to allow for water efficient fixtures. Empirical methods are typically seen in the form of a square root or regression curve, derived from water consumption data taken from various buildings varying in size and fixture quantities (Jack et al., 2017). Stochastic algorithms implement a time-series approach, making use of frequency sampling data obtained from user behavioural patterns (Wong and Mui, 2018). The work conducted by Jack et al. (2017) suggests that empirical model are more accurate in estimating peak flow rates when compared to probabilistic methods.

As evidence towards reducing water consumption and peak flow rates has grown, so has the need for the plumbing industries and international research community to define new and improved systems to estimate a specific building's peak flow rate. Blokker et al. (2010) developed a stochastic based model, SIMDEUM, that has been implemented as an empirical plumbing design curve within Dutch standard ISSO-55 (Jack et al., 2017). Using Monte Carlo simulations and fuzzy logic, Oliveira et al. (2013) offers a model to simulate end user behaviour at fine-scale time intervals, combining the accumulative water consumption to predict peak flow rates within buildings. Possibly the most adopted advancement toward the update of international plumbing codes and predicting peak flow rates is the work conducted by Buchberger et al. (2017), which exists within the appendices of the Uniform Plumbing Code (UPC:2018) (UPC) and has a user-friendly downloadable excel spreadsheet titled 'Water Demand Calculator' (WDC, https://www.iapmo.org/water-demand-calculator/). Through Monte Carlo simulations derived from US residential end-use studies (REUS), Omaghomi et al. (2020) demonstrated that a specific fixture probability of use (p-value) diminishes as building size increases. This has led to update to the WDC to include p-values as a function of fixture count.

Australian Cold-water Service Design Standards

Chance (2015) suggests that the current standing methods used in Australia are derived from British plumbing codes that implement an adaptation of the 'loading units' system developed by Hunter. British codes tally the total number of loading units of a downstream pipe and align this quantity against a probabilistic design curve to estimate a specific plumbing systems design flow rate (IoP/CIPHE, 2002). It is believed the British code was modified to suit the Australian climate (Chance, 2015), which eventually led to the Australian Institute of Plumbing publication titled 'Selection and sizing of copper tube for water piping systems' also known as the 'Barrie Book' (Smith, 1976). This informative design reference was then established as the basis for estimating peak flow rates, or probable simultaneous demand (PSD) within the National Construction Code (NCC) Volume Three – The Plumbing Code of Australia (PCA) deemed to satisfy (DtS) solution, (AS/NZS 3500.1:2018).

Over the past two decades, research into fixture end-user behaviour for single or detached residential dwellings has documented both an increased adoption of water efficient fixtures and a behavioural shift in water usage because of the Australian millennium drought (Beal and Stewart, 2011, Willis et al., 2011, Arbon et al., 2014). Yet in comparison, the methods used by practitioners to estimate PSD has gone unchanged for almost 50 years. Suggesting that the current Australian plumbing standard would significantly over-estimate design peak flows rates just as many comparable international plumbing standards and codes do also.

Understanding that the current methods within the industry standards may now be outdated, the ABCB commissioned a discussion paper through GHD (Chance, 2015). Although the paper has a primary focus towards 'fixture units' in sanitary plumbing and drainage systems, the paper has also outlined much of the research previously discussed. The ABCB has also presented alternate wording for future iterations of the PCA to allow for practitioners more flexibility in demonstrating that plumbing system meets performance-based requirements (Zeller and Ashe, 2019). Such an approach is known as a performance-based solution (PBS), and the proposed changes would allow for hydraulic designer to use any available method to estimate a specific building's peak hydraulic demand during the peak hour of water consumption. Currently the PCA offers two paths of acceptable design practice, 1) Design as per the PCA's DtS (AS/NZS 3500.1:2018) or 2) a PBS. Proposed cold-water service performance requirements in the upcoming PCA (NCC 2022-public comment draft) stipulates (ABCB, 2020):

- Pipework water velocity does not exceed 3m/s for more than 1% of the time that water is required during the annual peak hour,
- A cold water service must ensure working pressures at outlets are:
    - not less than 50kPa and not more than 500kPa;
    - where working pressures outside the range specified in (a) are required, working pressures suitable for the correct functioning of the fixture or appliance,

A template for a performance-based solution has been developed by the HCAA (HCAA, 2020). For a PBS to be considered compliant, all relevant stakeholders must agree and sign off on the proposed solution. Yet, companies may display reluctance to adopt a performance-based solution outside of the nominated DtS solution because limited evidence supporting the suitability of alternate methods used within Australia and the exposure to litigation (Chance, 2015).

To assess the suitability of a PBS, the ABCB is investigating the implementation of the VM in future revisions of the PCA to compare estimated peak flow rates. The VM employs a modified formula, derived from the work conducted by Robert Wistort (Buchberger et al., 2017). Wistort hypothesized that the number of fixtures running water in a building follows a binomial distribution having the mean and variance described by Eq. (1) and Eq. (2) respectively.

$$\mu = np = n\frac{t}{T} \quad \textbf{(1)}$$

$$\sigma^2 = np(1-p) = \frac{nt(T-t)}{T^2} \quad \textbf{(2)}$$

where:

- μ is the mean of the busy fixtures,
- σ^2 is the variance of the busy fixtures,
- n is the number of fixtures in the building,
- p is the probability that an individual fixture is running water,
- t is average duration of demand,

- T is the time between successive operations of the fixture,

The probable simultaneous flow rate ($PSFR$) is estimated as the 99th percentile of the demands assuming a normal distribution as shown in Eq. (3).

$$PSFR = \sum_{k=1}^{K} \frac{n_k t_k q_k}{T_k} + z_{99} \sqrt{\sum_{k=1}^{K} \frac{n_k t_k {q_k}^2 (T_k - t_k)}{{T_k}^2}} \tag{3}$$

where:

- K is the total number of fixtures groups along a down-stream pipe,
- n_k is the number of fixtures for a specific fixture group downstream of a pipework section,
- q_k is the specific fixture flow rate,
- t_k is the average duration of usage in seconds,
- T_k is the time between successive operations of an individual fixture in seconds,
- z_{99} is the 99th percentile of the standard normal distribution, approximated as 2.326.

Currently fixture probability is flexible, where parameters t_k and T_k can be adjusted by hydraulic designers to suit a specific building's application. In many current international plumbing codes, however, probability values are fixed and are the same for all buildings (Zeller and Ashe, 2019).

Buchberger et al. (2017) suggest that the Wistort methodology may be better suited to buildings with larger fixture counts. Adding further complication, data regarding fixture probabilities of use is limited in Australia and is also a function of building size (Omaghomi et al., 2020). It is noteworthy to mention that the newly developed WDC (version 2.0) uses the same algorithm developed by Wistort, yet does not allow for any adjustment to fixture probabilities when calculating the 99th percentile flow rate for residential buildings.

WATER DEMAND INVESTIGATION

To ascertain if the current Australian plumbing standard over-estimates peak flow rates in multi-level residential buildings, HCAA initiated a long-term project to monitor actual water consumption of four buildings located in Sydney and Canberra in 2019 to present day. In the current research, recorded peak flow rates for each building are compared against the Australian plumbing standard, the ABCB's VM and comparable international plumbing codes. In addition to this, flow rate frequencies are assessed to establish the amount of time buildings were subjected to 'peak usage periods'.

Flow Monitoring Device and Configuration

At each building the main residential cold-water distribution pipes were fitted with Flexus F501 ultrasonic flow meters (FLEXIM, Edgewood, NY: https://www.flexim.com/) capable of recording a flow rate range of 0.01m/s to 25m/s with a repeatability of 0.25% and measurement uncertainty of ±1.5% at a reading of ±0.01m/s. To enable long-term monitoring, pulse emissions were set to 1 pulse/3L of volumetric flow. Data is acquired at 5-second intervals, but only the 1-minute average values of the (previous 12) acquisitions are logged and sent to a Cloud storage via GSM network. The minimum recording flow rate was set to 0.1m/s, where all logged values below this threshold default to a value 0m/s. Data were then downloaded in '.csv' format and arranged into flow recordings for each day and time in 1-minute intervals.

Peak Flow Rate Adjustment

After a review of relevant research regarding the logging of high-resolution flow rate data, there is no consensus toward an accepted temporal resolution to capture peak hydraulic events. In addition, wording used by international plumbing codes such as 'instantaneous' or 'simultaneous' is vague and does not define a specific length of time that a peak event would be captured over. The temporal resolution used in previous international studies varies between 1-second to 30-seconds (Tindall and Pendle, 2015, Bleys et al., 2012, Stråby et al., 2019, Douglas, 2019). Soriano et al. (2016) noted that the monitored building's daily peak flow rate was observed over a 15-second period.

The current study uses a 1-minute temporal resolution to monitor water consumption. For tap and toilet use specifically, the total time of usage is usually less than 30-seconds, suggesting that peak flow rates may be diluted because of a 1-minute logging frequency. Whilst an in-depth investigation towards this topic is outside the scope of the current research, an evaluation of HCAA pilot study water consumption data captured at 15-seconds intervals for a 146-residential-apartment building in NSW showed that when a moving average was applied over four data acquisitions, 1-minute data would require an adjustment factor of 1.18 to account for the dilution of peak flow events captured at 15-second intervals. In the current study, measured peak flow rate will be adjusted ("corrected") by a conservative factor of 1.3 to account for any dilution associated to a 1-minute logging frequency.

Building Information

All four monitored buildings were constructed after 2013 and are fitted with water efficient appliances, rated between 3 and 6 stars compliant to water efficiency labelling and standards (WELS) in Australia. Summarised in Table 2, is each of the monitored building's information regarding occupancy, apartment counts and respective fixtures counts. Building profile information was collated through plumbing design documentation and building management records obtained for each site.

Table 2 – HCAA Building Fixture Counts

Site Location, Monitoring Period & Estimated Occupancy	Bedrooms	Bathrooms	Kitchen Sink	Dishwasher	Laundry Tub	Washing Machine	Shower	Basin	Toilet	Bath	Urinal	Apartments	Total Apartments	Total Fixtures
Site 1: Waterloo, Sydney, NSW 13th-August-19 to 14th-March-20 Estimated Occupancy: 90%	252	239	145	143	143	143	239	239	239	-	-	145	[a]143	1291
Site 2: Milsons Point, Sydney, NSW 17th-October-19 to 14th-March-20 Estimated Occupancy: 90%	228	228	123	123	115	123	228	254	230	27	-	123	123	1223
Site 3: Manhattan, Canberra, ACT 14th-December-19 to 14th-March-20 Estimated Occupancy: 95% (15% of apartments are 'short term' stay)	522	524	330	330	330	330	527	536	525	4	-	331	[b]330	2912
Site 4: Braddon, Canberra, ACT 17th-January-20 to 14th-March-20 Estimated Occupancy: Unknown	189	158	124	-	117	115	150	178	171	2	2	117	[c]115	859

Notes:

[a] Total apartment count excludes common space.

[b] Total apartment count excludes gym.

[c] Total apartment count excludes ground floor and level 1.

Peak Flow Rate Comparison

Presented in Figure 2, measured and adjusted peak flow rate for each building was compared against the current Australian plumbing standard AS/NZS 3500.1:2018, the ABCB's VM, the German standard (DIN 1988-300, 2012) and International Association of Plumbing and Mechanical Officials (IAPMO) WDC (version 2.0) developed by Buchberger et al. (2017). When estimating the 99th percentile flow rate using the ABCB's VM, the probability of use for each specific fixture's values for t_k and T_k was taken from residential fixtures detailed within the worked example presented by Lucid Consulting Australia (2019).

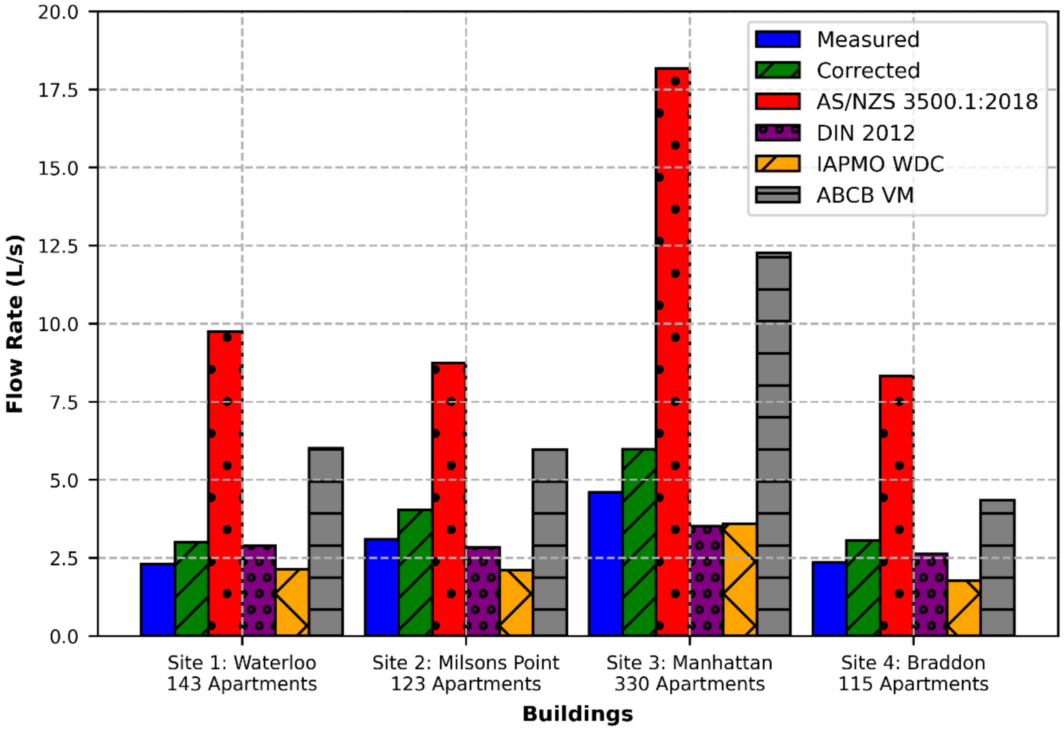


Figure 2 – Measured and corrected (multiplied by a factor of 1.3) peak flow compared against Australian and International plumbing codes that predicted 99th percentile design flow rates

As shown in Table 3, considering corrected flow rate values of the four monitored building, the current Australian plumbing standard over-estimates peak flow rates between 217-326%.

For all buildings, the current German standard and IAPMO WDC displayed an apparent "under-prediction" for corrected flow rate values. However, it is worth noting that measured and corrected flow rate values are absolute peak flow rates, where comparatively each code attempts to define the 99th percentile flow. When evaluating only the peak hour of water consumption for each building, the 99th percentile flow for each building (see Table 3) would see a reduction between 28.3-40.1% from measured peak values. Considering only measured 99th percentile flow rates, the IAPMO WDC displayed the greatest accuracy in predicting design flow rates, with an average over prediction of 11.2%.

Whilst the ABCB's VM demonstrates a reduction from the current Australian standard, it still presents significant over estimation in comparison to measured and corrected flow rate values when implementing the probability values adopted by Lucid Consulting Australia (2019). This suggests further work is required in defining the probability of fixture use values that accurately represent the Australian climate.

Table 3 – Water investigation flow rates compared to Australian and International plumbing codes

Site [Monitoring Days]	Apartments	Fixtures	Measured	[a] Corrected	[b] 99th Percentile Flow	AS/NZS 3500.1:2018	DIN 1988-300:2012	IAPMO WDC	ABCB VM	[c] % AS/NZS 3500.1 Overestimation
1 Waterloo, Sydney, NSW [215]	143	1291	2.3	2.76	1.65	9.74	2.88	2.13	6.01	326%
2 Milsons Point Sydney, NSW [149]	123	1223	3.1	3.75	1.85	8.74	2.84	2.10	5.96	217%
3 Manhattan Canberra, ACT [92]	330	2912	4.6	5.52	3.75	18.2	3.52	3.59	12.3	304%
4 Braddon Canberra, ACT [58]	115	859	2.35	2.82	1.50	8.33	2.62	1.76	4.35	273%

Notes:

[a] Corrected value assume 1.3 of measured values.

[b] Assumes 99th percentile flow within peak hour of water consumption for all monitoring days.

[c] Percentage calculated using corrected values.

Flow Rate Frequency

To demonstrate the range and relative time each building spent at various hydraulic conditions, flow rate data was arranged into clusters of 0.1L/s, see Figure 3. Most observed flow rates are in a state of low flow, with more than 90% of flows rates observed were less than 1.0L/s for sites 1, 2 and 4 and 2.0L/s for site 3. Daily peak events were only captured over one data acquisition (less than a minute) and each building respective 99th percentile flow (within the peak hour of water consumption) is between 63.8-81.5% of measured peak flow rates. Douglas et al. (2019) suggests that current design methodology considers only ‘zero flow’ and ‘peak flow’ scenarios. However, flow rate data presents significant variation in hydraulic conditions. This suggests the future design methodology should not only consider but give a stronger bias towards ‘low flow’ conditions that dominate the observed flow rate data sets.

To highlight the extent of peak flow rate over-estimation within each building, flow velocity limits for standard type B copper pipes are displayed within Figure 3. Pipe velocity limits assume an industry practice of 1.5m/s. This is based on the International Copper Association Australia (2015) recommended flow velocity range of 1.5m/s-2.1m/s for operation under peak conditions. Each building’s nominal main residential cold-water pipe is DN100. Yet, when considering the observed flow rate data, sites 1,2, and 4 could be reduced to a DN40 pipe, and site 3 a DN50 pipe. These pipe sizes would result in flow velocities intermittently exceeding the recommend operation of 1.5m/s flow velocity for copper pipes but still comfortably meet the requirements of the 3m/s flow velocity limit set within AS/NZS 3500.1.

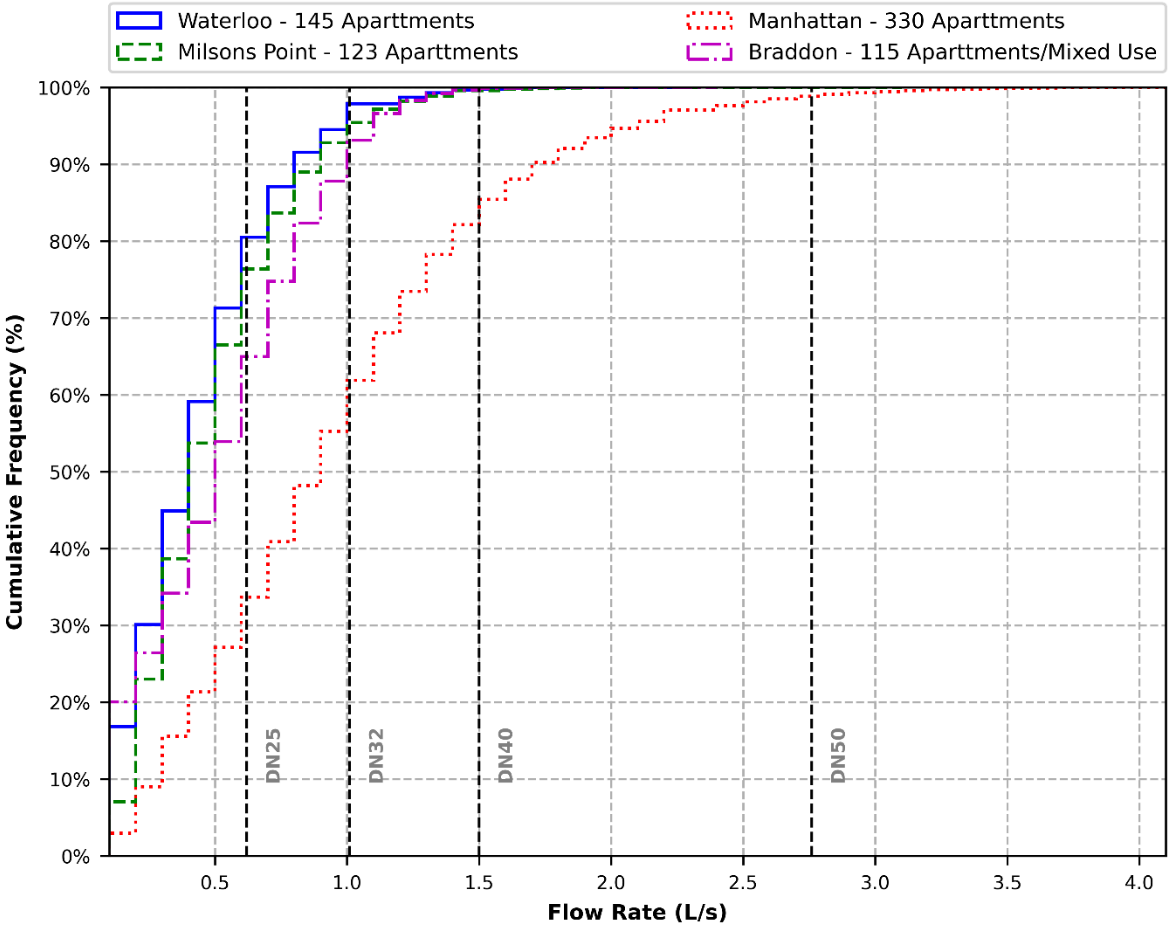


Figure 3 – Cumulative distribution of flow rates observed in monitored buildings, shown against alternative pipes sizes assuming 1.5m/s flow velocity (e.g. 1.5L/s flow will result in ~1.5m/s velocity in DN40 copper pipes).

HYDRAULIC MODELLING – A CASE STUDY

Much of the standing international research into the estimation of peak flow rates in multi-level residential building considers only that peak flows are over-estimated. Whilst this is a very noteworthy finding associated to plumbing network design, studies rarely consider the implications of a size reduction towards a plumbing network. The opportunity to install smaller pipework, booster pump systems and plumbing hardware is attractive from a commercial and environmental standpoint. Yet, an unavoidable by-product of a reduce system size will be increased flow velocities. The undesirable effects of velocity-based events such as cavitation, throttling of flow due to trapped air or water hammer (pressure surges) may then be exacerbated when compared with the current oversized systems.

Moreover, in Australia, there is a lack of regulatory requirements to validate proposed plumbing designs outside typical steady-state pipe flow parameters such as flow rate, pressure and flow velocity when using methods defined within AS/NZS 3500.1. In most cases, system design is only assessed under assumed peak hydraulic conditions, with inadequate consideration to varied states of demand and a plumbing system's lifecycle performance and efficiency.

To gain a deeper understanding of current hydraulic conditions and performance within multi-level residential apartment buildings, a case study of a specific apartment building's cold-water service has been conducted through numerical modelling. Only the steady-state condition is considered in the current research. The developed hydraulic model has generated results for various scenarios built in Bentley Software's "Openflows WaterGems" (Bentley Systems Incorporated, 2019). To provide relative results, building schematics and hydraulic design drawings have been obtained for Site 1, Waterloo building, where water usage and pipe flows have been monitored as a part of the Hydraulic Consultants Association of Australasia (HCAA) water demand investigation (WDI). A comparison between anticipated peaks flows determined by AS/NZS 3500.1 against stochastic rectangular pulse water demand model, validated by measured peak flows obtained from the HCAA's WDI, has been conducted.

Method

The following section outlines the methodology used for the hydraulic modelling and identifies relevant modelling scenarios and assumptions. Modelling conducted assessed various hydraulic scenarios of a cold-water service model that was developed for the nominated building is Site 1, Waterloo NSW (cold-water service). This site was selected after a review of the available design data obtained for all four sites. The design information for the Waterloo site was deemed more complete, which resulted in less modelling assumptions required to complete the case study.

System Configuration

A simplified plumbing layout is presented in Figure 4. The selected building's residential cold-water service can be split into two system categories, 1) major system and 2) minor system. The major system includes three main risers to supply water to each level's water meter cupboard and heated water storage tanks located on respective building tower's rooftop. The minor system includes the downstream plumbing of each water meter cupboard that separates into induvial DN20 pipes to supply each apartment with cold-water.

The developed model will assess the residential cold-water service from the variable-speed pump set located on basement level 2 (relative level 19.5m) to each apartment on each respective level/tower, as well as final demand nodes simulating heated water storage units located at the top of towers B and C (relative level 58m). Each ‘node’ shown in Figure 4 represents a water meter cupboard, where a junction from the main riser is located 1.5m above floor level and then splits again into a series of DN20 pipes to supply the building’s apartment with cold-water.

Modelled cold-water service consists of 1 pumping station, 981 copper pipe elements; ranging from sizes of DN25 to DN100, 35 pressure reducing valves, 145 20mm water meters modelled as general-purpose valves and 795 junctions with 147 water demand nodes that supplies the 145 apartments and 2 hot-water storage units throughout the 3 respective towers.

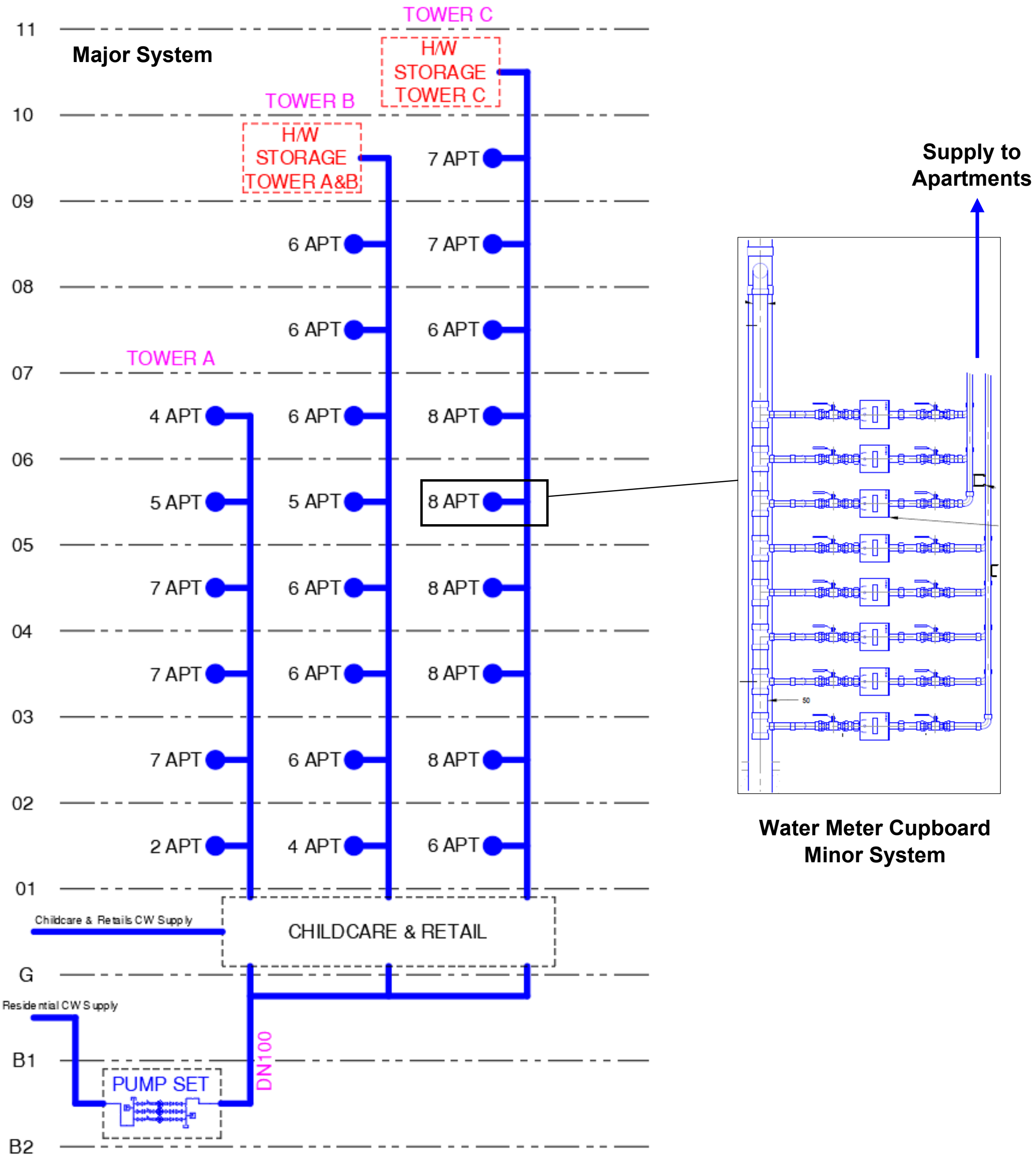


Figure 4 – Site 1, Waterloo: Simplified cold-water service layout.

Modelling Scenarios

The hydraulic modelling considers two conditions of flow, 1) single period and 2) extended period. Four scenarios in total are considered and they are nominated as:

1) AS/NZS 3500.1: single period
2) Monitored: single period
3) Monitored: extended period
4) Resized: extended period

The single period scenarios assess a constant flow rate at the time of peak water consumption to emulate typical plumbing design practice that gives little consideration toward varied states of flow. The extended period flow scenarios evaluate hydraulic performance over a three-hour period with 10-second time steps to simulate a single morning's peak period of water consumption.

Each modelling scenario assesses typical plumbing parameters such as flow rate (demand), pipe flow velocity and pressure. In addition, consideration to hydraulic profile, system losses and pump operating parameters have been evaluated. Modelling conducted does not consider transient events for unsteady states of flow.

- **AS/NZS 3500.1: Single Period**

This scenario is used to develop a baseline of results for comparison by reviewing the intended design conditions of the building and assesses the performance at a single time step with building a peak flow rate of 9.75L/s.

- **Monitored: Single Period**

To provide insight towards observed hydraulic conditions, the plumbing performance over a single time step is simulated using peak flow rate like those seen from the HCAA water demand investigation.

- **Monitored: Extended Period**

Building on the results of the single period scenario, the "monitored: extended period" scenario assesses the range of hydraulic conditions experienced over a morning period of peak water usage.

- **Resized: Extended Period**

To consider a future state of plumbing design, the major system (all pipes before water meter cupboards) and pump set are resized, where pipe flow velocity cannot exceed the limit of 3m/s in accordance with AS/NZS 3500.1.

The re-sized system involves a significant size reduction in pipe diameter. DN100 pipes are reduced to DN40 pipes, DN80 pipes are reduced to DN32, DN40 pipes to DN25 and all other pipes are reduced to DN20.

In the instance of the minor plumbing system, pipes sizes remain the same as they are already at the minimum pipe size of DN20 defined by AS/NZS 3500.1 where the internal diameter (ID) of a pipe cannot be smaller than 15mm from the property service to branch offtakes.

Plumbing System Losses

Major Losses

For major pipe losses, the hydraulic modelling engine is set to use the Darcy-Weisbach where the friction factor for turbulent flow is solved iteratively using the Colebrook-White formula (Bentley Systems Incorporated, 2018). The modelled plumbing network assumes type B copper pipe and an associated Darcy-Weisbach roughness height (ε) of 0.0015mm (Cengel and Cimbala, 2014). Presented in Table 4 is the nominal dimensions of copper pipe sizes used.

Table 4 – Type B copper pipe sizes (International Copper Association Australia, 2021)

Nominal Size	Tube Size	Internal Diameter	Safe Working Pressure
DN20	19.05 x 1.02mm	17.01mm	3,970 kPa
DN25	25.40 x 1.22mm	22.96mm	3,500 kPa
DN32	31.75 x 1.22mm	29.31mm	2,780 kPa
DN40	38.10 x 1.22mm	35.66mm	2,300 kPa
DN50	50.80 x 1.22mm	48.36mm	1,710 kPa
DN65	63.50 x 1.22mm	61.06mm	1,370 kPa
DN80	76.20 x 1.63mm	72.94mm	1,520 kPa
DN90	88.90 x 1.63mm	85.64mm	1,300 kPa
DN100	101.60 x 1.63mm	98.34mm	1,200 kPa

Minor Losses

Presented in Table 5 are the list of system losses used for hydraulic modelling. Minor losses use default values set within WaterGEMS. Depending on the configuration, more than one definition of pipe loss can occur, such as flow through a tee-branch and a reduction in pipe size. In these instances, pipe losses are added together for a combined total of minor losses.

Table 5 – Minor pipe losses used in hydraulic modelling

Description	Loss
90° Bend r/R =1	0.370
Tee - Branch Flow	1.280
Tee - Line Flow	0.350
Contraction - Sudden D2/D1 = 0.20	0.490
Contraction - Sudden D2/D1 = 0.50	0.370
Contraction - Sudden D2/D1 = 0.80	0.180
Valve - Gate (Open)	0.390

Plumbing Hardware

Critical plumbing hardware devices are modelled through a general-purpose valve (GPV) within WaterGEMS (Figure 5). GPV's enable a head loss curve to be developed as a function of flow rate. Modelled plumbing hardware includes:

- 100mm reduced pressure zone device (RPZD) for backflow prevention,
    - 40mm RPZD for hydraulic modelling conducted for resized scenario,
- 20mm cold water meter,
- Pressure reducing valves (PRV) located along main residential cold-water service,
- Pressure limiting valves (PLV) located upstream of cold-water meters for levels one and two.

For RPZD's head loss curves were derived from commercially available products (Apollo Valves, 2021a, Apollo Valves, 2021b).

Cold water meters are derived from American Water Works Association (AWWA) standards assuming a ¾" water meter (Hunter Industries, undated). Because system pressures at PRV and PLV locations exceeded pressure limits, head losses associated to flow through the device are irrelevant because the system model defaults to the pressure limit. Because of this, PRV and PLV head losses from flow are ignored. The PRV pressure limit for the main residential cold-water supply is 500kPa and the PLV pressure limit for apartments on levels one and two is 350kPa (as per design documentation).

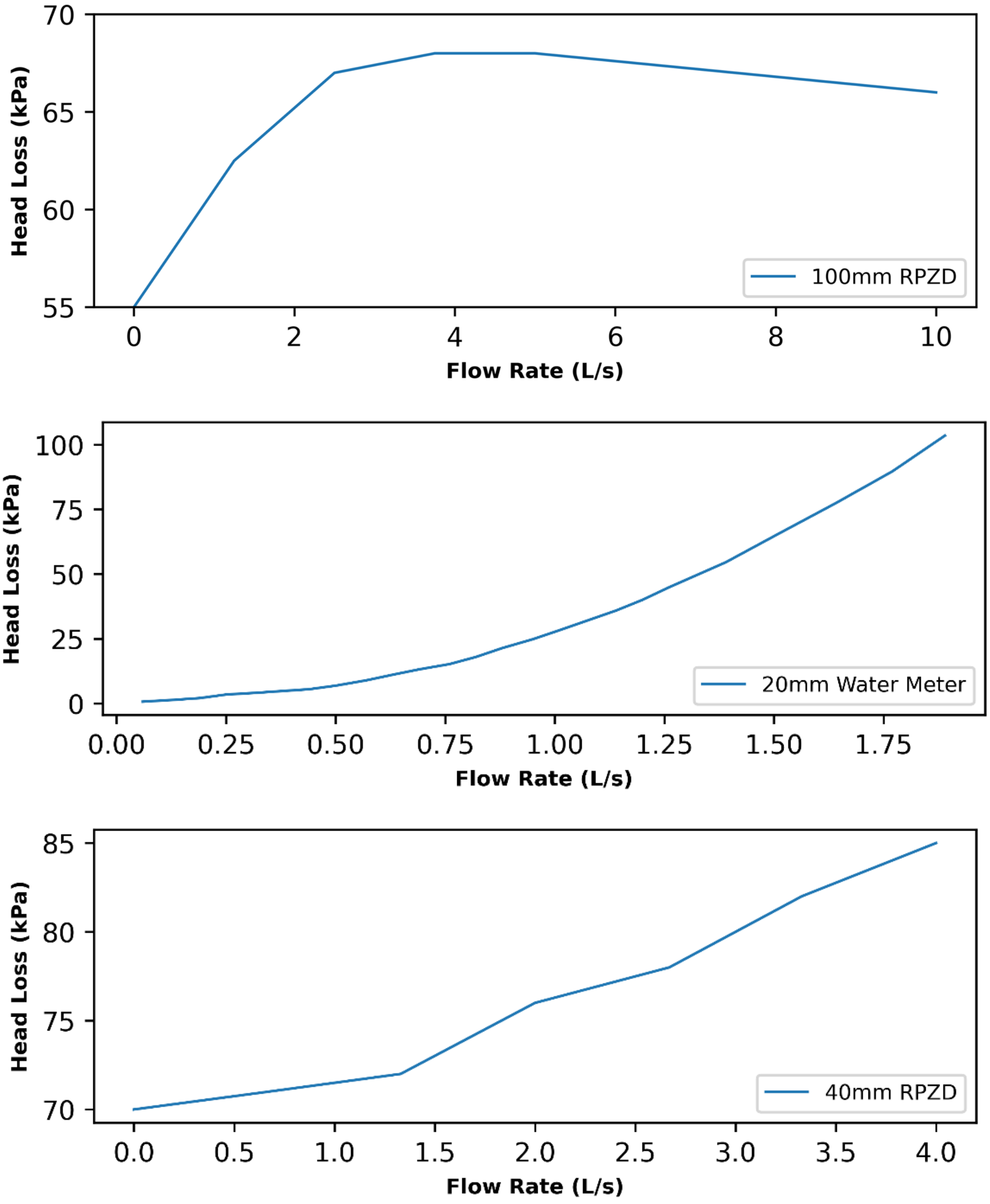


Figure 5 – Plumbing hardware headloss (kPa) curves as a function of flow rate (L/s)

Pumping System

Water main data supplied specifies a minimum pressure of 38m head and a maximum pressure of 59m head, resulting in a potential differential of 21m head that the pump set is required to account for. For all hydraulic modelling scenarios, the minimum available head of 38m is used to simulate available pressure at peak morning periods.

When referring to AS/NZS 3500.1 ‘as built’ detail design drawings, the pump set specified is a ‘*triplex variable speed potable cold-water booster pumps*’ with a nominated pump duty of ‘*5L/s at 350kPa’* for each pump.

The booster pump systems consist of three inline vertical variable speed pumps connected in parallel to deliver water throughout a building’s cold-water service. System configurations are set for a ‘lead’ pump to supply a desired flow at a nominated best efficiency point (BEP), with the remaining pumps operating as ‘lag’ to make up the difference in required flow rate. The hydraulic model is set to replicate this configuration using a ‘target pressure’ setting, at which a control node at the most hydraulicly disadvantaged apartment is selected for the system to maintain a required pressure. In accordance with design documentation, the minimum pressure required at an apartment node is 250kPa.

AS/NZS 3500.1 and Monitored Scenario (As Built) Pump System

With reference to supplied pump quotation documentation, the nominated pump model for the waterloo site is Xylem Lowara cold-water triplex pressure system, Model GHV30-15SV04F040T with three e-SV vertical multi-stage pumps, model number 15SV04F040T, 4kW (2890rpm). Pump curves were derived by using multipoint head and efficiency taken from the manufacturers pump performance curve (see Appendix - Pump Performance Curves) into the WaterGEMS pump calculation engine. Pump curves for the as built pumping system is shown in Figure 6.

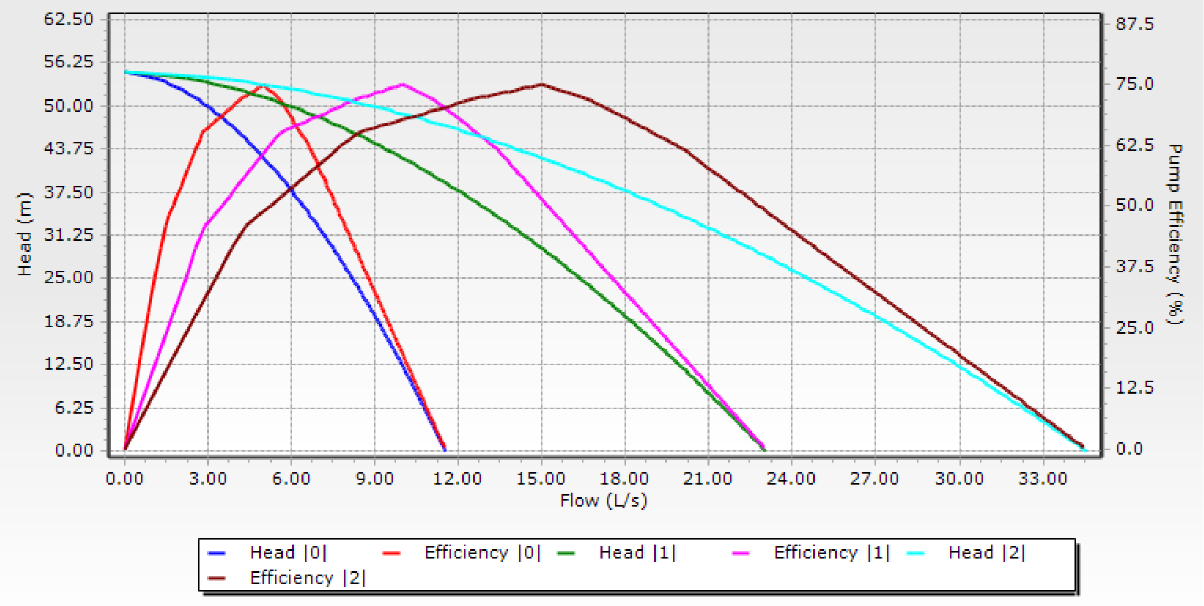


Figure 6 – ‘As built’ pump definition curves for hydraulic modelling. (|0|= one pump, |1|=two pumps, |2|= three pumps)

Resized Pump System

The pump system selected for ‘resized’ modelling scenario uses the same manufacturer, with a reduced system capacity. Pump selection was conducted by using Xylem’s pump sizing calculator (Xylem, 2021). To replicate the pump selection for the ‘as-built’ pumping system, parameters entered considered two pumps to operate at 2.84L/s at a duty of 65m head, with an additional pump on stand-by for peak periods (3 pumps total). The nominated pump is Lowra 5SV12 with a duty of 1.68/s at 598kPa with an efficiency of 67.2%.

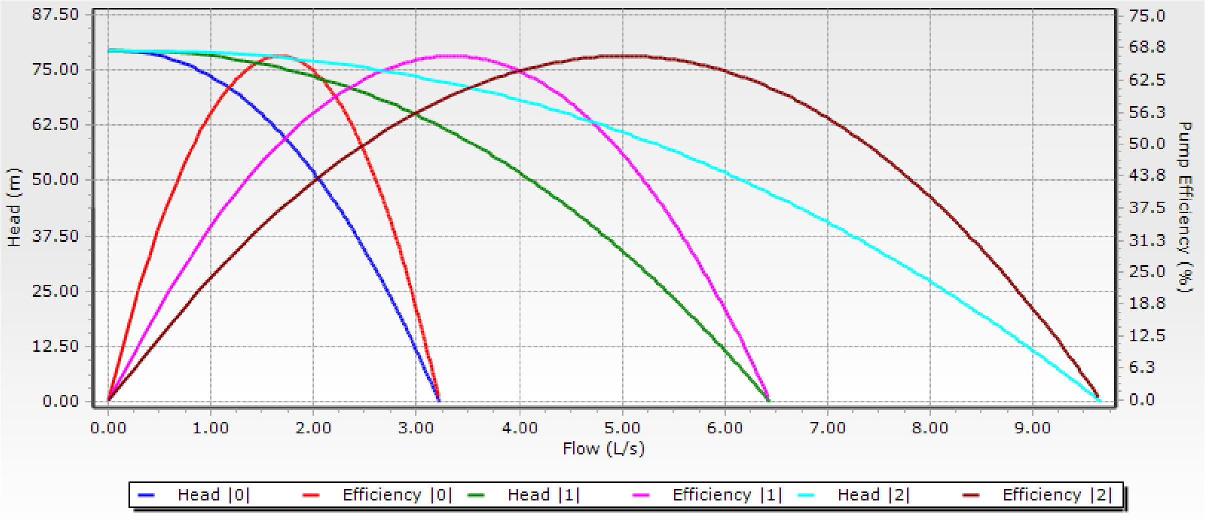


Figure 7 – 'Resized' pump definition curves for hydraulic modelling. (|0|= one pump, |1|=two pumps, |2|= three pumps)

Apartment Water Demand

A stochastic based model is developed using Python script to simulate residential apartment water usage, implementing specific household fixture usage event data presented in the South East Queensland Residential End-Use Study (Beal and Stewart, 2011) (SEQREUS). Model results are used as a comparison against the selected monitored building data obtained from the HCAA's water demand investigation.

The SEQREUS collected water consumption data of 252 residential dwellings throughout four major regions of the South-East Queensland area, adopting a mixed method approach that combined the use of high-resolution 'smart' water meters. Fixture use events were disseminated via the application of event recognition software. Monitoring of water consumption was combined with water appliance audits alongside household water usage diaries to differentiate individual behaviour patterns. Data obtained was the result of three separate monitoring periods conducted during winter 2010, summer 2010/2011 and winter 2011 (Beal and Stewart, 2011).

Where data is limited with respect to water consumption for multi-level residential buildings at a household and fixture level, Jordán-Cuebas et al. (2018) suggests indoor fixture usage data obtained from residential end-use studies offers a viable source of secondary information for evaluating water consumption in multi-level residential buildings. This approach has been adopted by Blokker et al. (2010) for the development of SIMDEUM and the before mentioned water demand calculator (Buchberger et al., 2017).

Total Water Demand

The demand model is used to generate ten different apartment total demands (Figure 8) that considers both hot and cold-water usage. For each of the 145 apartments, one of the ten demand patterns is randomly assigned to an apartment assuming equal probability. The random generation runs until the peak hydraulic demand is within +/-10% of the selected building's corrected peak flow rate of 2.76L/s (monitored scenarios) and design flow rate 9.74L/s (AS/NZS 3500.1 scenarios).

When generating the monitored scenario demand patterns, to obtain flowrates near 2.76L/s, each apartment is given a 50% chance to select a demand pattern, where an apartment that fails to select a demand pattern would default to zero demand. Comparatively, the AS/NZS 3500.1 scenario assumes a 100% chance of selecting a demand pattern.

For monitored single period scenarios, the peak flow rate is 2.92 L/s, where demand consists of 28 apartments drawing a cold-water peak of 1.22L/s and 23 apartments drawing a heated water peak of 1.70L/s simultaneously. For the AS/NZS 3500.1 single period scenario, the simulated peak flow rate is 9.75L/s, where 56 apartments draw cold-water for a total of 8.35L/s and 31 apartments draw heated water for a total of 1.3L/s.

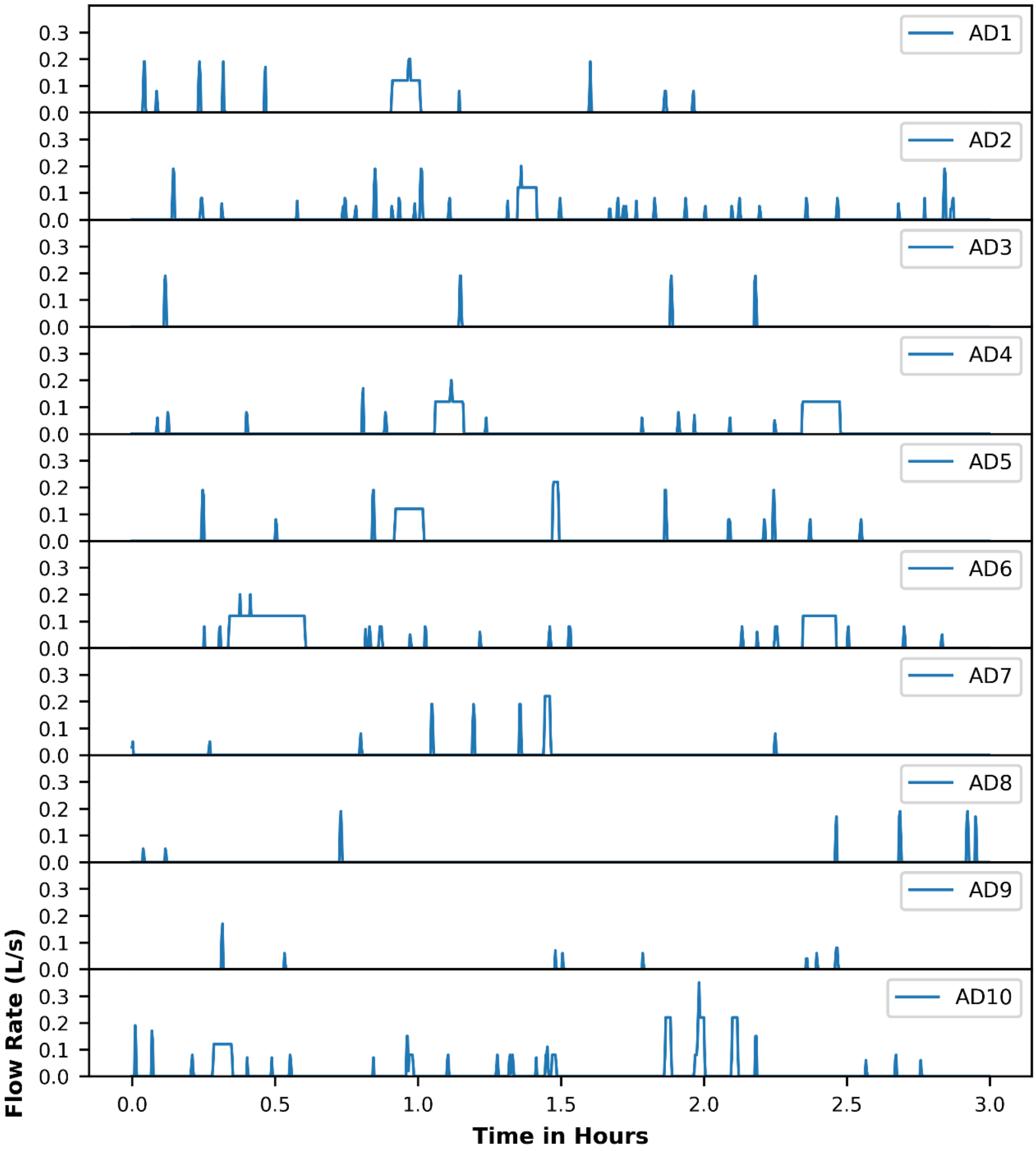


Figure 8 – Simulated apartment total water demands used for hydraulic modelling

Hot and Cold-Water Demand

Because of the configuration of plumbing network layout, hot and cold-water demands are split between direct apartment use (cold-water only) and heated water storage units. Demand for all cold-water usage goes to a specific apartment node and the heated water portion is diverted to the associated heated water storage tank to replace the heated water theoretically consumed at a specific fixture within the apartment.

Hot and cold-water demands are calculated as a constant percentage of a specific fixture's total demand. Hot and cold-water demand percentages are presented in Table 6 and were derived from a US based residential end use study that evaluated the percentage of hot-water and cold-water use between specific fixtures (DeOreo et al., 2016). Hot-water demand for apartments 1-77 (78 apartments) are assigned to the hot-water storage unit for towers A & B and apartments 78-145 (67 apartments) are assigned to the heated water storage unit on tower C (Figure 4). Developed extended period modelling scenario's total water building demand and heated water demands for towers B and C are shown in Figure 9.

Table 6 – Hot and cold water fixture demand percentages (DeOreo et al., 2016)

Fixture	Cold Water Demand	Heated water Demand
Shower	33.8%	66.2%
Tap	43.0%	57.0%
Baths	40.9%	59.1%
Toilet	100.0%	0.0%
Clothes Washer	80.0%	20.0%
Dishwasher	100.0%	0%

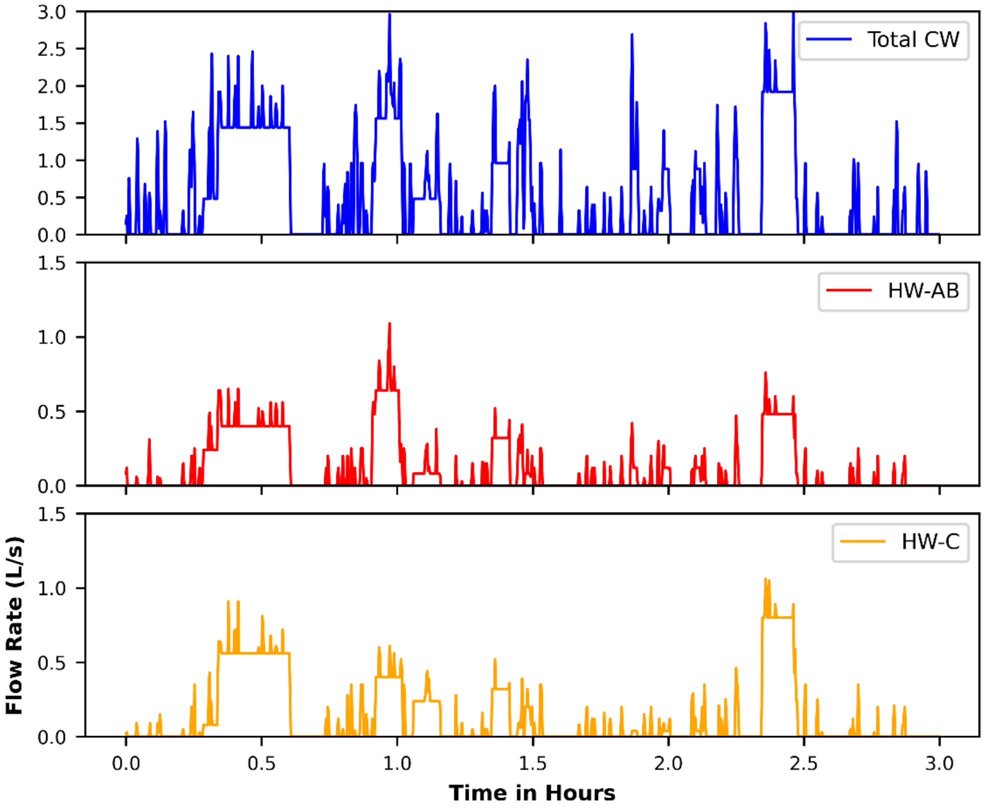


Figure 9 – Simulated extend period demands for total cold-water, heated water tower-AB and heated water tower-C

Demand Model

In its current state, the developed model considers only influence from household behaviours towards fixture usage and does not disseminate between number of occupants, specific apartment fixture configurations or socio-demographic factors that influence water consumption. The occupancy levels obtained from the SEQRUES over the three metering periods for the various sub-regions were between 2.4-3.0 people in each dwelling, with an aggregated average of 2.7 people per household. Based on ABS Census data and building information, this may lead higher water consumption as the average occupancy levels for apartments buildings (four levels or greater) recorded 1.9 people in each dwelling (Australian Bureau of Statistics, 2018).

The modelled water usage pattern follows rectangular pulses model described by Buchberger and Wells (1996). Using an adapted equation presented by Blokker et al. (2010), building simultaneous flow rate (L/s) at any specific time is described by equations (4) & (5):

$$q_t = \sum_{a=1}^{B} \sum_{k=1}^{F_{ak}} P(I_{akt}, D_{akt}, \tau_{akt}) \tag{4}$$

$$P(I_{akt}, D_{akt}, \tau_{akt}) = \begin{cases} I_{akt} & \tau_{akt} < T < \tau_{akt} + D_{akt} \\ 0 & elsewhere \end{cases} \tag{5}$$

where, a, k and t are indices; t = specific time interval of day (seconds); a =all building apartments from 1 to B; k =all end-uses from 1 to F_{ak} (the frequency of usage for apartment, a and fixture use, k); I =pulse intensity (flow rate L/s); D =pulse duration (seconds); τ =time when fixture use begins. Therefore, D_{akt} = duration for end use, k, for the apartment, a, at time, t. The resulting pulse function, $P(I, D, \tau)$, is equal to the pulse intensity, I, at time at which fixture begins operation, τ to $\tau + D$ and 0 (zero) during all other time periods. The summation is completed for all (B) building apartments and for the frequency of use (F), resulting in the measurement of volumetric flow rate, q (in units of L/s), at specific time interval, t.

Presented in Figure 10 is the process the stochastic model simulates a single apartment's daily water usage. Figure 11 shows a specific example of the resulted daily water usage by a single apartment. To determine the pulse function, for each fixture, the number of events, volume, duration, and time of use are selected using the parameters listed in Table 7 and associated probability distribution for a specific fixture's time of use (Figure 12). This process is repeated for the number of specified apartments, *(B)* within the building. Each flow event at a specific time of day (seconds) is combined to produce a simultaneous building flow rate for each specific time of day (q_t). To develop aggregated data on simulated water usage, this process is repeated to replicate 50 days *(n=50 trials)* of total building water usage.

Shown in Figure 12 is the developed weighted probabilities associated to the time of use for specific fixture events. Time of use probability values are developed using average hourly fixture consumption (L/p/h/d) data from the three monitoring periods during the SEQREUS (Beal and Stewart, 2011). Hourly fixture consumption data is then averaged between the three monitoring periods and normalised against the total volume to determine the probability distribution.

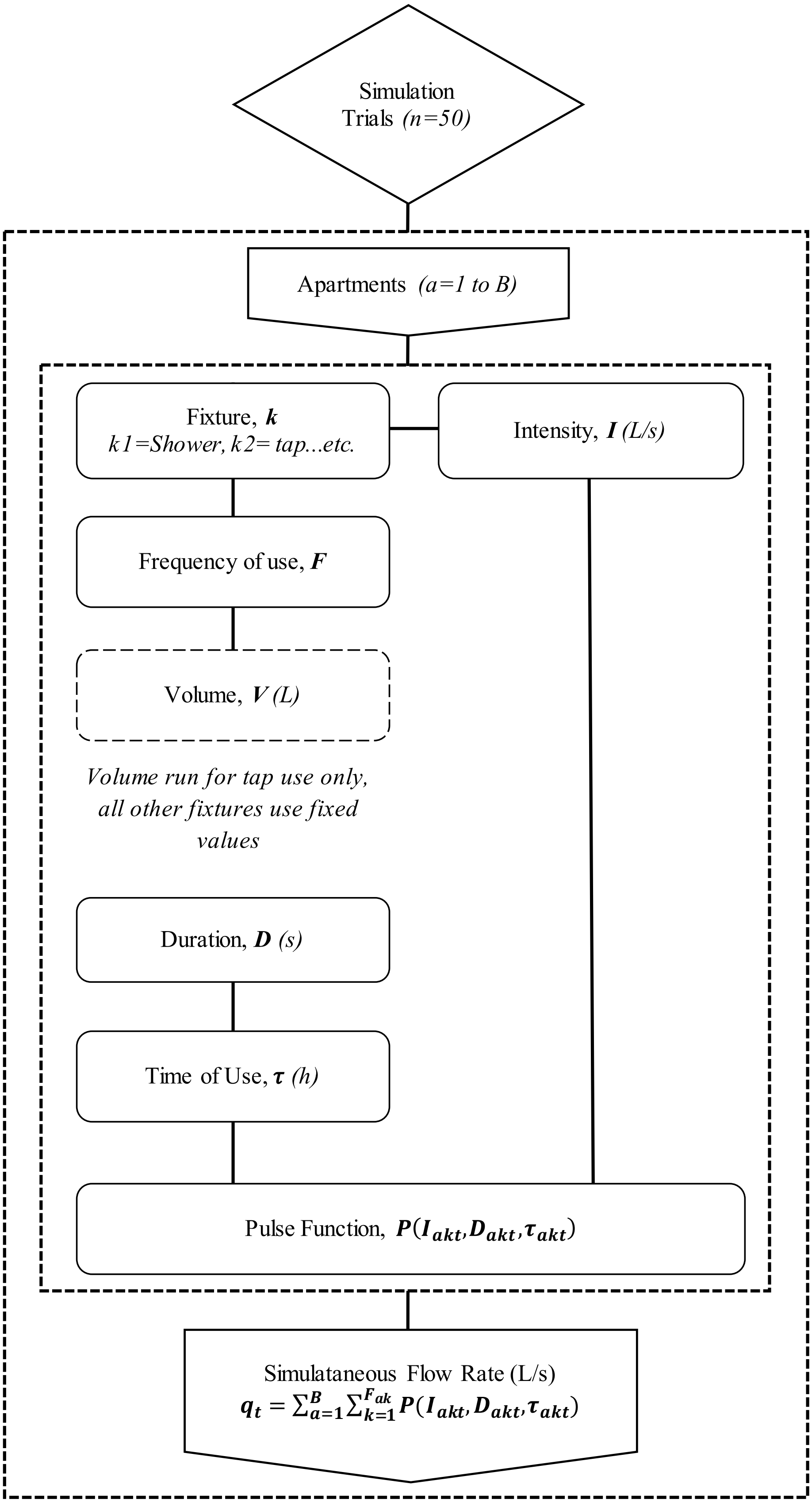


Figure 10 – Stochastic water demand model simulation processes

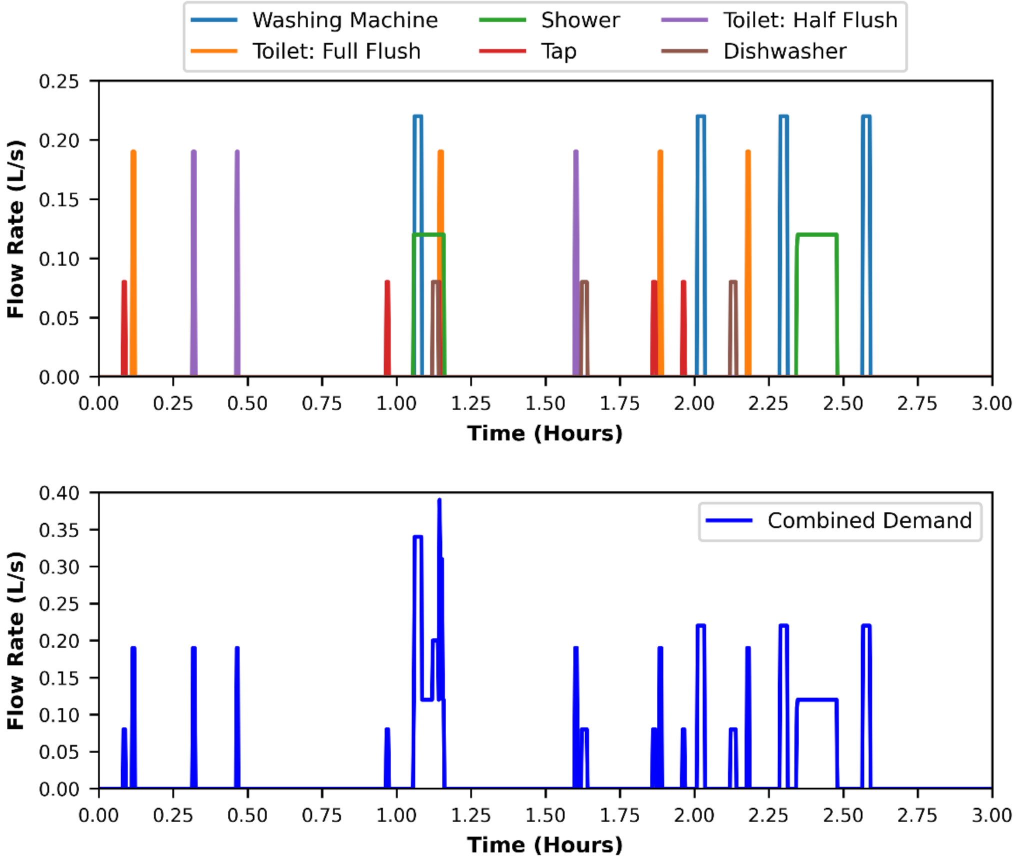


Figure 11 – Example of simulated daily apartment demand for each specific fixture and combined demand

Table 7 – Stochastic water demand parameters

	Shower	Tap	Toilet (half flush)	Toilet (full flush)	Washing Machine	Dishwasher	Bath
Frequency, F (ul)							
Range:	0-8	0-135	0-14	0-18	0-2.75	0-4	0-1
Average:	2	48.8	4.1	5.5	0.6	0.5	0.1
Intensity, I (L/s)							
Flow Rate:	0.12	0.08	0.19 [b]	0.19 [b]	0.22 [b]	0.08 [b]	0.2
Volume, V (L)							
Range:	N/A	N/A	Fixed	Fixed	Fixed	Fixed	Fixed
Average:	N/A	0.39[a]	4.5	3	67	14.1	95
Duration, D (s)							
Range:	30-900	N/A	Fixed	Fixed	Fixed	Fixed	Fixed
Average:	480	N/A	24	16	76[c]	59[d]	475
Time of Use, τ (h)							
AM Peak:	7	8	8	8	9	9	10
PM Peak:	18	19	19	19	14-18	20	18
PCA Maximum:	[e]9L/min	[e]9L/min	[f]6L	[f]3L	N/A	N/A	N/A
Design flow rates, AS/NZS3500.1:	0.10L/s	[g] 0.10L/s	0.10L/s	0.10L/s	0.20L/s	0.20L/s	0.30L/s

Notes:

[a] Tap volume corrected based on water efficient fixtures in (Beal and Stewart, 2011)

[b] Flow rate assumes upper limit from Water Demand Calculator (Buchberger et al., 2017)

[c] Repeated for 4 cycles over a two-hour period.

[d] Repeated for 3 cycles over a two-hour period.

[e] Fixture flow rate water efficiency performance metric set within PCA (ABCB, 2020).

[f] Fixture volume water efficiency performance metric set within PCA (ABCB, 2020).

[g] Assumes aerated tap (AS/NZS 3500.1:2018).

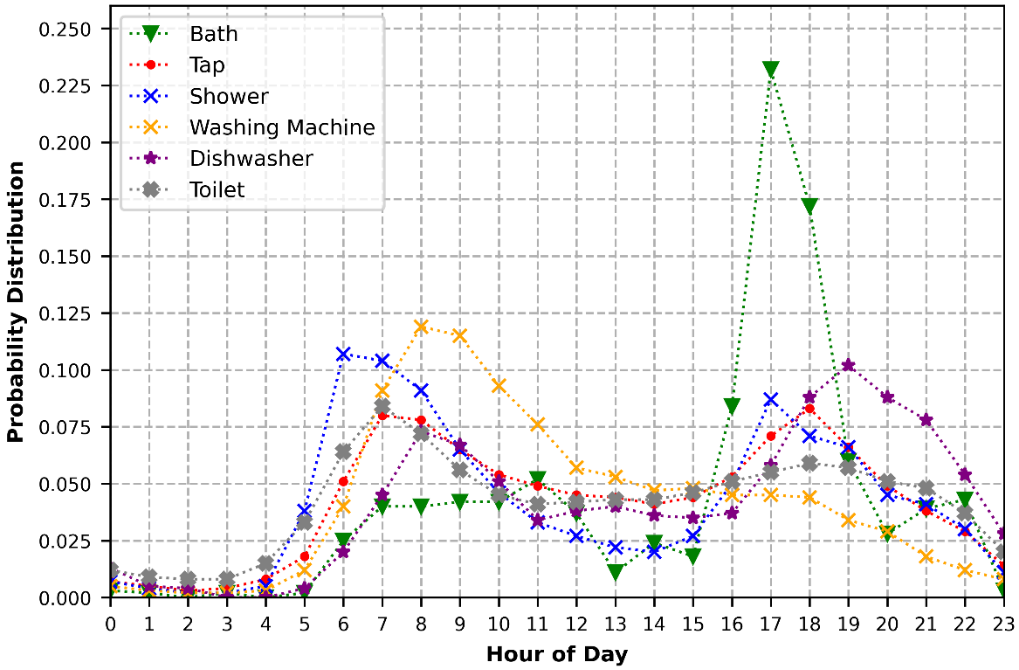


Figure 12 – Weighted probabilities for fixture time of use

Demand Model Validation

To demonstrate the suitability of the demand model, 50 days of simulated water usage for a 145 multi-level residential apartment building is compared against the 215 days of observed flow rate data obtained for site 1: Waterloo, NSW. To evaluate the same temporal resolution, 1-second simulated data is converted to 60-second average data by taking the average flowrate value for every 60 data points.

Plotted in Figure 13 is the 99th percentile and 50th percentile flows for both the modelled and observed data sets for each hour in a day. The modelled data is agreeable for the AM peak periods but displays greater demand in the PM peak period. The peak flow rates of the modelled (60-second data) and observed data are 2.23L/s and 2.30L/s respectively (not shown), demonstrating that the developed model offers comparable morning peak demand for application within the hydraulic model.

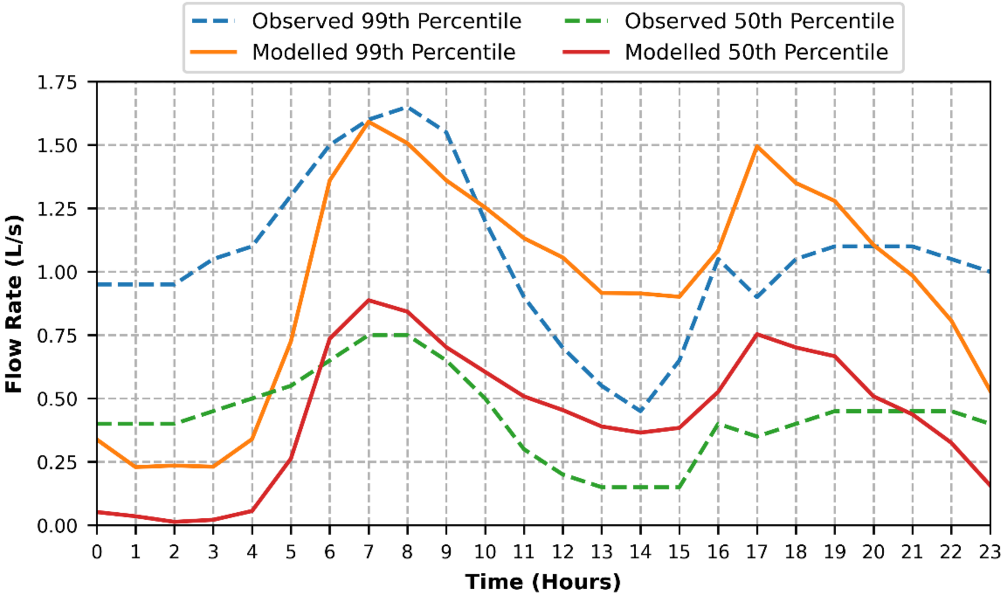


Figure 13 – 99th and 50th percentile flows for each hour of day for 50 days of simulated water usage versus 215 days of water consumption for a 145 residential apartment building

Results

Single Period Hydraulic Modelling

Single period scenarios are simulated to determine if a significant gap exists in hydraulic conditions between an assumed design state of peak flows determined by AS/NZS 3500.1 and the monitored peak flow rates observed during the HCAA's water demand investigation. Results displayed compare the flow rates, pipe flow velocity, pressure loss and a snapshot of the building's hydraulic profile.

Flow Rates

Figure 14 displays the cumulative frequency of peak flow rates experienced in all pipes within the developed hydraulic model. Because of the limited observational period the single period analysis conveys, greater than 50% of pipes experience zero flow for both AS/NZS 3500.1 and monitored scenarios. The peak flow rates experienced were 9.75L/s and 2.84L/s and average flow rates were 0.47L/s and 0.14L/s for AS/NZS 3500.1 and monitored scenarios, respectively.

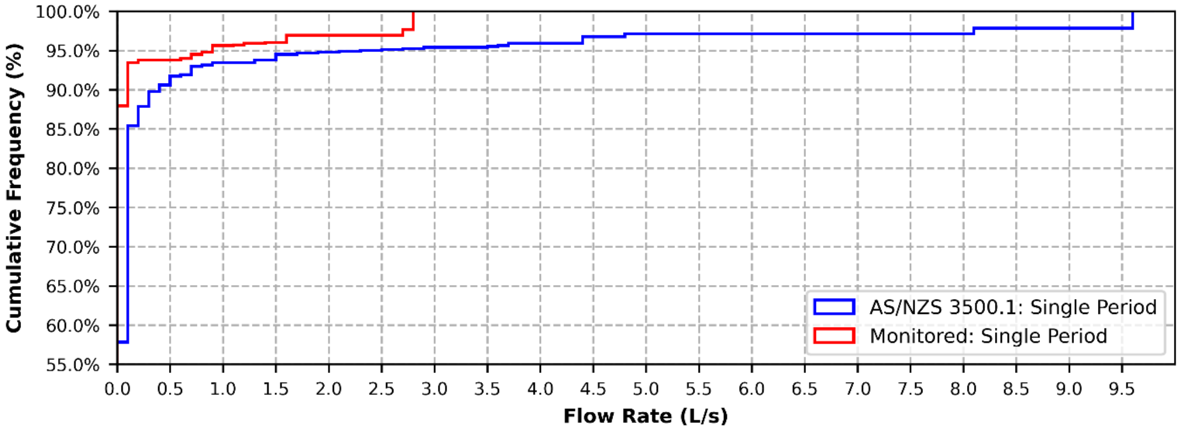


Figure 14 – Cumulative frequency plot of pipe flow rates for AS/NZS 3500.1 and monitored single period hydraulic modelling scenarios

Pipe Flow Velocity

Comparative cumulative frequencies of modelled pipe flow velocities for single period scenarios are displayed in Figure 15. Maximum flow velocities were 2.4m/s and 1.4m/s for AS/NZS 3500.1 and monitored scenarios, respectively. However, these peak values exist through the pumpset and the modelled 50mm diameter steel pipes on the suction and discharge sides of the pumps. Excluding these values, the peak velocity values were 1.28m/s (AS/NZS 3500.1) and 0.37m/s (monitored).

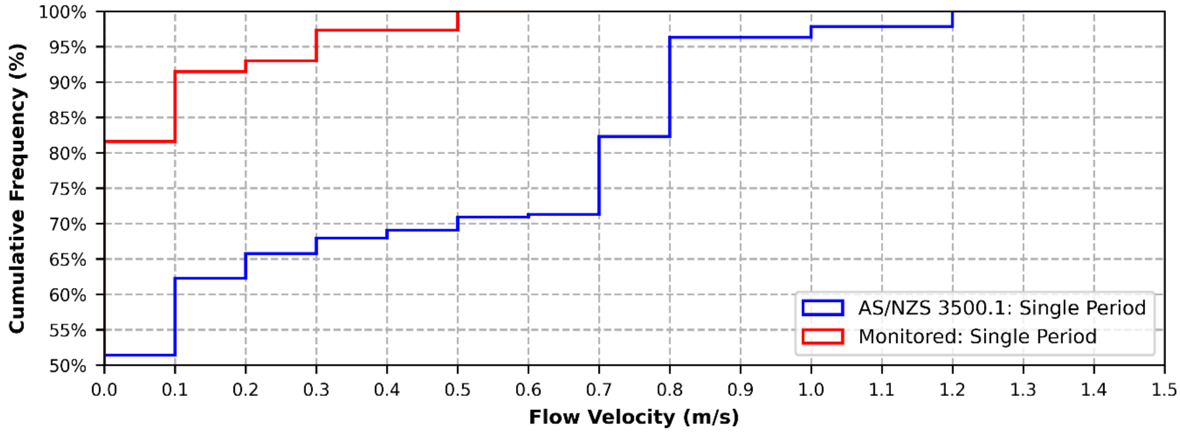


Figure 15 – Cumulative frequency plot of pipe flow velocity for AS/NZS 3500.1 and monitored single period hydraulic modelling scenarios

Pipe Pressure Loss

Presented in Figure 16 is cumulative frequency plots for AS/NZS 3500.1 and monitored single period pressure loss experienced in pipes due to fluid flow and minor losses (loss from change in elevation is excluded). The maximum pressure loss for AS/NZS 3500.1 single period scenario was 7.95kPa and 3.52kPa for the monitored single period scenario.

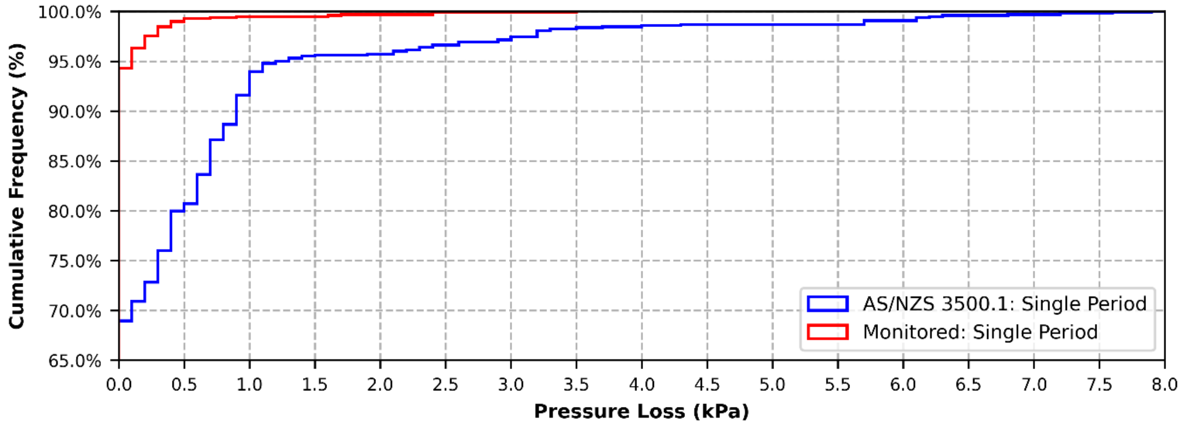


Figure 16 – Cumulative frequency plot of pipe pressure loss for AS/NZS 3500.1 and monitored single period hydraulic modelling scenarios

Hydraulic Profile

A review of the available pressure at each level for the waterloo building’s three main risers is presented in Figure 18. Bar charts display the available pressure at each junction upstream of each water meter cupboard when operating under peak flow rate conditions. Lines overlapping the bar charts display the relative level (RL) in meters for junction.

Variation in available pressure between the two single period scenarios is insignificant with a maximum variance of 2.57%. Noteworthy changes to the hydraulic profile can be seen at the pump set duty. For the AS/NZS 3500.1 single period scenario, two pumps operating at a duty of 4.88L/s and 30.27m head was required to maintain 250kPa at the most hydraulicly disadvantaged apartment node on level 9 on, Riser C. Comparatively the monitored scenario required one pump to supply 27.47m head at a duty of 2.84L/s. Pump relative speed and operating efficiency values for AS/NZS 3500.1 and monitored scenarios were 0.886 at 69.6% and 0.752 at 66.52% respectively.

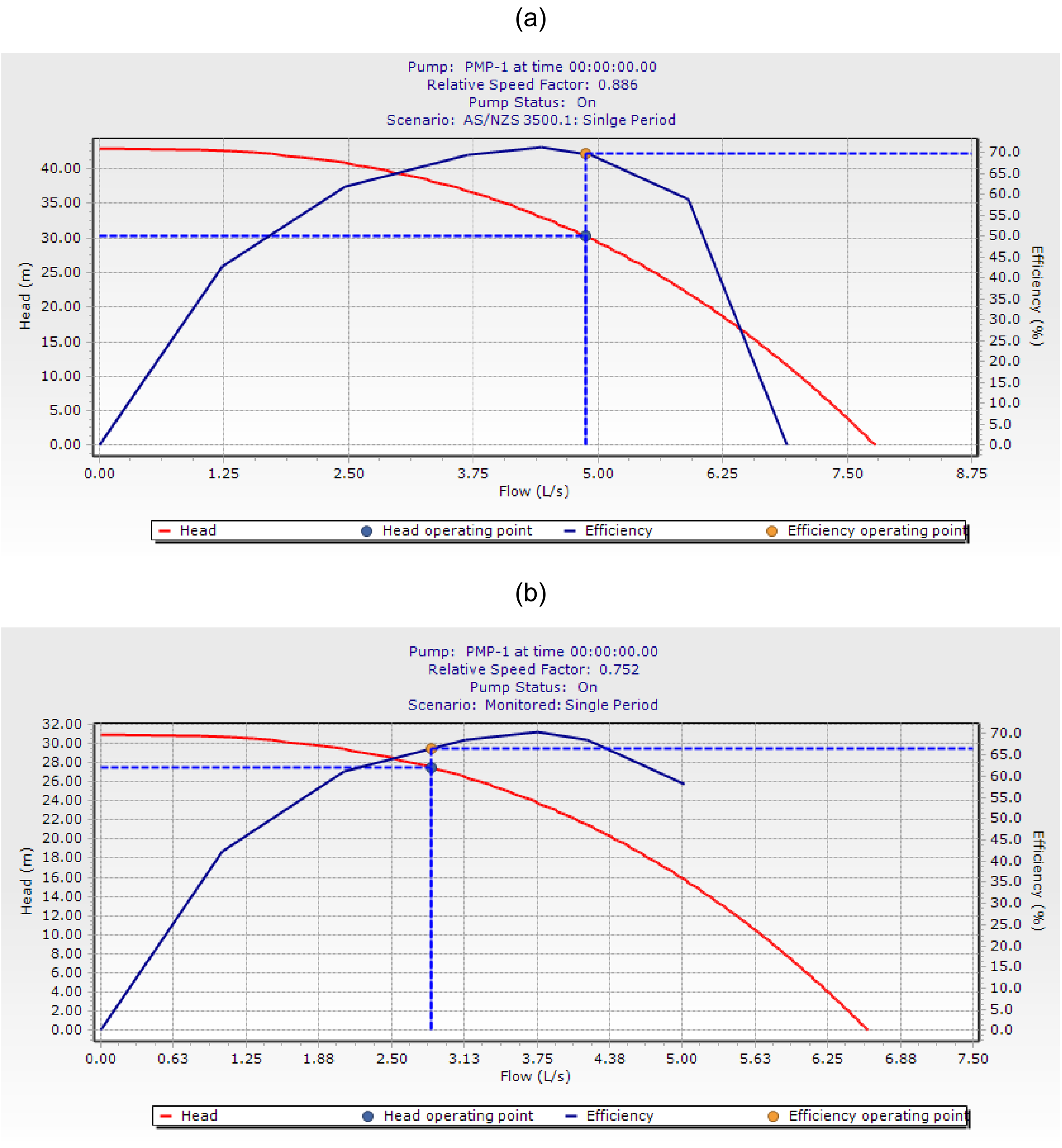


Figure 17 – Pump performance curves for (a) AS/NZS 3500.1 and (b) monitored single period scenarios

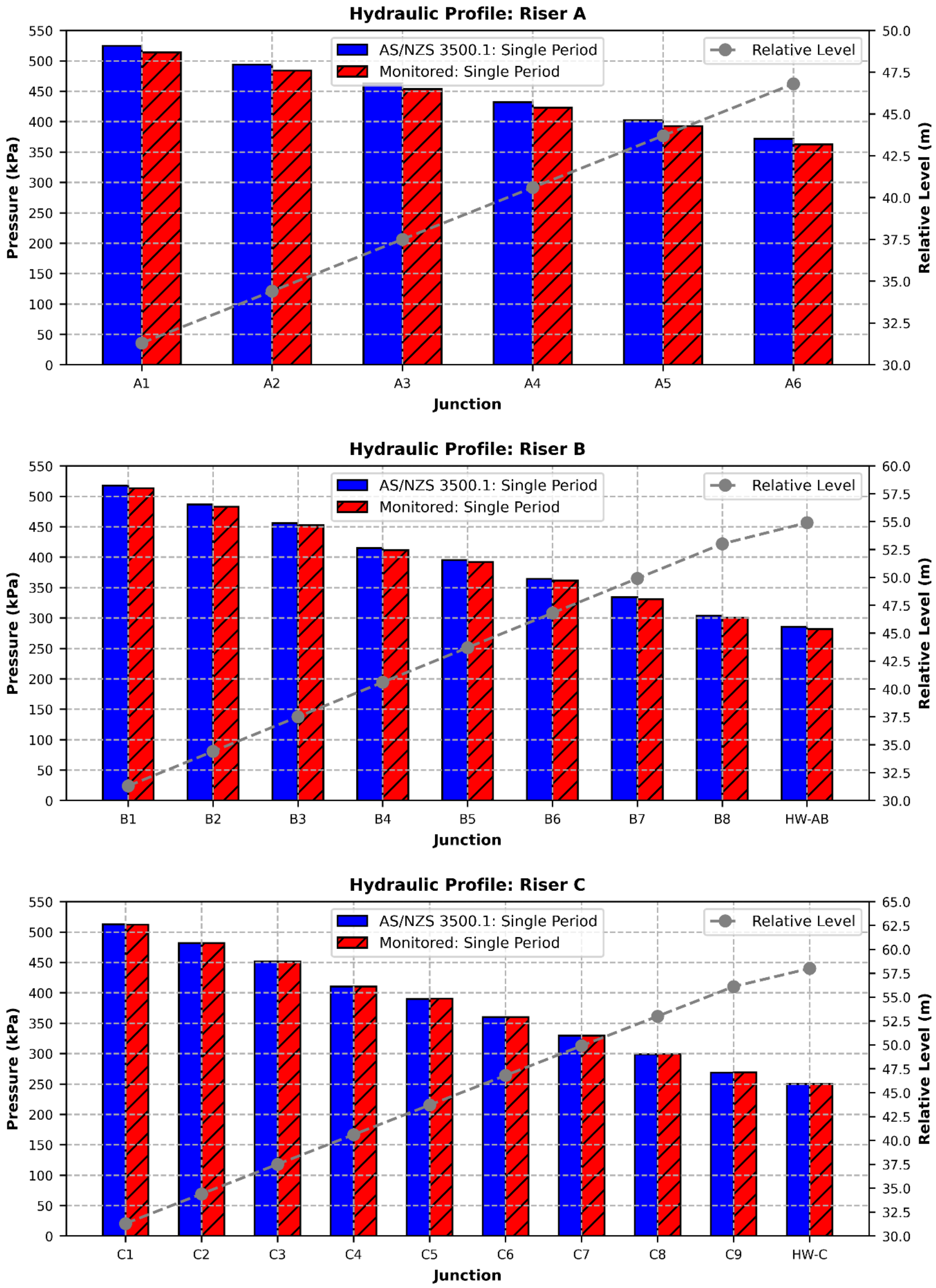


Figure 18 – Hydraulic profiles for risers A, B & C for AS/NZS 3500.1 and monitored single period hydraulic modelling scenarios

Extended Period Hydraulic Modelling

Extended period scenarios nominated as ‘monitored’ and ‘re-sized’ simulate a singular 3-hour morning peak period of water consumption. Extended period scenarios considered both the current ‘as-built’ (monitored scenario) cold-water service and a reduced size (re-sized scenario). The re-sized scenario intends to replicate possible future design practices where it is likely that as newer methodology to predict peak flow rates are adopted by industry, plumbing systems will be designed with lower hydraulic loads and as a result, the size of pipes, pump sets, valves and appurtenances will reduce.

Results presented consider pipe flow rates, pipe flow velocity, and dynamic pressures. In addition, consideration toward pump operating efficiency and the operating conditions of plumbing valves and hardware is reviewed.

Flow Rates

Presented in Figure 19 are the line diagrams for flow rates experienced in the cold-water pipes nominated as 1) main cold-water residential, 2) Riser A, 3) Riser B, and 4) Riser C. To present the full demand of each riser, the downstream pipe immediately after the cold-water supply separates from the main cold-water service is displayed.

Both extended period simulations used the same demand pattern that was made up of 28 apartments drawing from 10 different randomly generated demand patterns with a peak flow rate of 2.92L/s. The maximum flow rates for risers A, B and C were 0.87L/s, 1.58L/s and 1.66L/s, respectively. When considering cold-water demand for single apartments, the peak flow rate was 0.35L/s aligned with apartment demand pattern ‘AD10’.

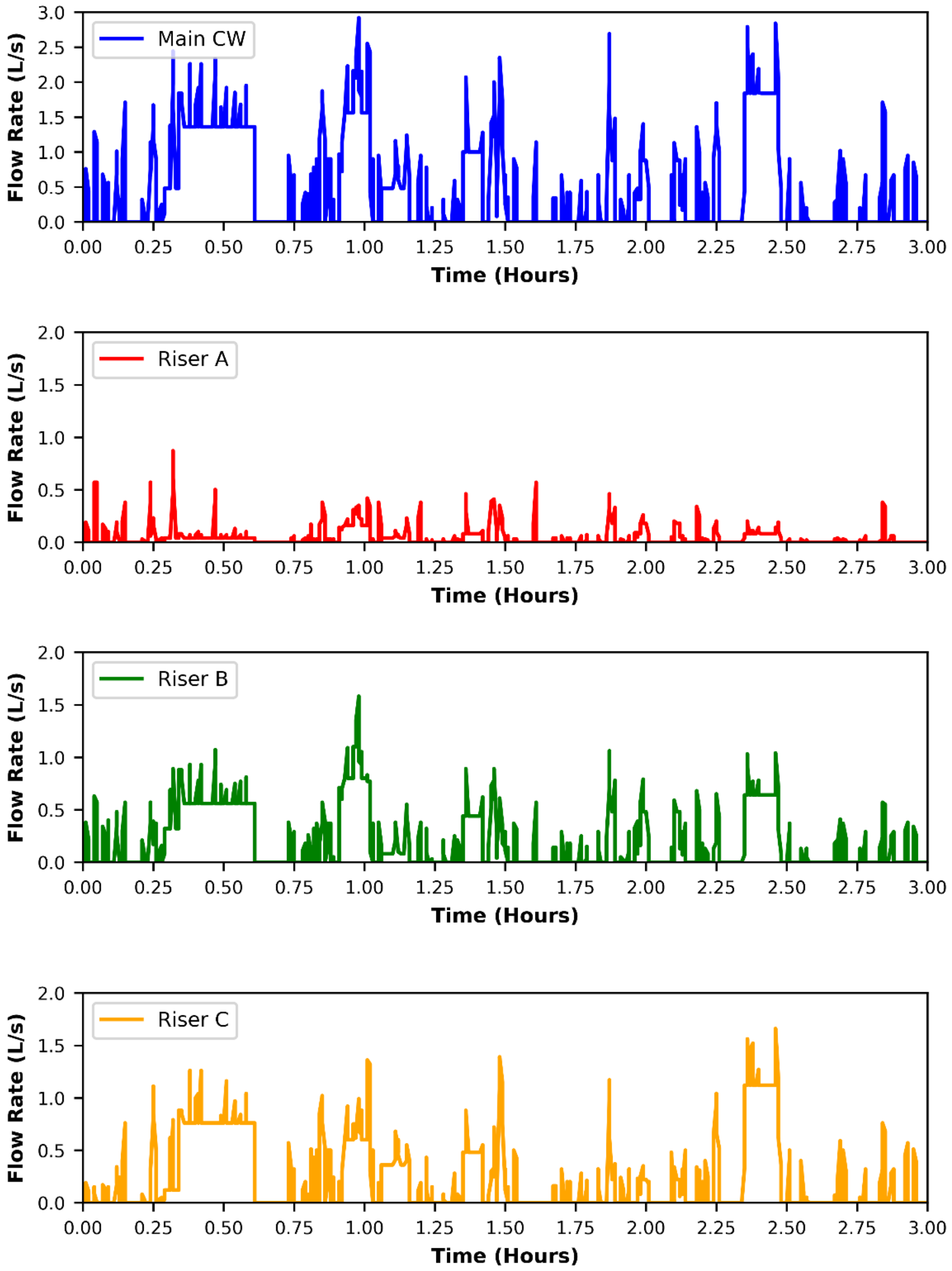


Figure 19 – Flow rates experienced in main cold-water, riser A, riser B and riser C pipes during extended period hydraulic modelling

Pipe Flow Velocity

To demonstrate the variance in flow velocity experienced between the monitored and re-sized extended period scenarios, velocity values within pipes for the building's main cold-water, riser A, B, and C are displayed in Figure 20. In addition to the resulting flow rate velocities, recommended operational velocity for copper pipes (1.5m/s) and velocity limit defined in AS/NZS 3500.1 (3m/s) are overlayed in charts presented in Figure 20.

For monitored extended period scenario, the peak flow velocity was 1.14m/s observed within the building's minor plumbing network supplying cold water to a specific apartment through a DN20 pipe. When only considering the major plumbing network, the maximum flow velocity observed was 0.57m/s. For the pipes evaluated in Figure 20 (main cold-water and base of each riser), flow velocity never exceeded 0.40m/s. The modelled values are lower than International Copper Association Australia (2021) recommended minimum flow velocity value of 0.50m/s to prevent the deposition of undesired suspended solids in pipes.

As expected, the reduced system size demonstrates an increase to flow velocity. A maximum flow velocity of 2.92m/s was observed within the main cold-water supply pipe for the re-sized extended period scenario. The maximum value satisfies the design requirements of AS/NZS 3500.1 where the maximum flow velocity must not exceed 3.0m/s.

A review into flow-induced failures of copper pipes was conducted by Roy et al. (2017), but it was unable to determine an optimal flow velocity. From an industry perspective, when sizing copper pipes designers in Australian generally limit the flow velocity to 1.5m/s. When evaluating this metric, the main cold-water pipe would exceed a flow velocity value of 1.5m/s for 11.4% of the time over the 3-hour peak period. Moving down-stream to each specific main riser, the time spent on operating at a value greater than 1.5m/s was seen to reduce to between 0.1% and 5.9% of the 3-hour period. Peak velocity values experienced in risers A, B and C were 2.10m/s, 2.34m/s and 2.46m/s respectively and were observed over one 10-second period.

The comparison between monitored and re-sized extended period modelling highlights the significant over-sizing of cold-water services present in multi-level residential buildings that leads to low flow rates experienced in buildings. The limited research conducted suggests the impacts of 'low flow' within buildings may lead to build up of entrained air (Bhatia, 2015), reduced water quality and premature failure of plumbing hardware (Farooqi et al., 2009).

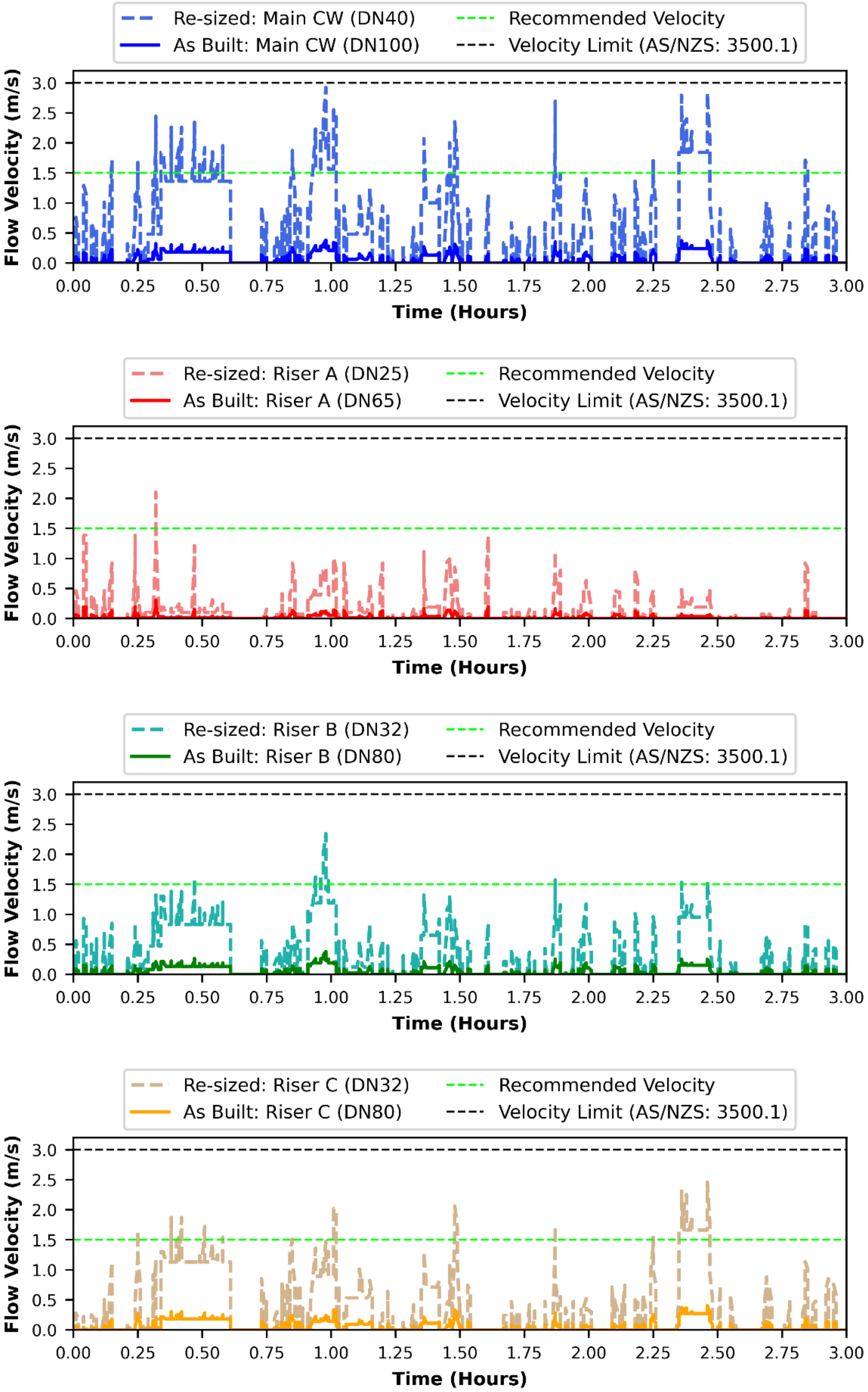


Figure 20 – Flow rate velocities experienced in main cold-water, riser A, riser B and riser C pipes during extended period hydraulic modelling with recommended (1.5m/s) and design (3m/s) velocity limits

Hydraulic Profile

To assess the difference in hydraulic profiles between monitored and re-sized extended period scenarios, the pumping head required to maintain pressures is assessed. Presented in Figure 21 and Figure 22 is the comparative head supplied to the cold-water service for each respective pump set.

When reviewing results, it should be noted that for the monitored extended period scenario, the design pump duty is well more than the actual peak flow rates experienced. As a result, only one pump is active to supply the required demand. Comparatively, the re-sized system pump set has been selected with the intent for at least two pumps to operate at the peak demand, with an additional pump on stand-by should anticipated peaks be exceeded.

Results demonstrates that as flow velocity's increase because of a reduced system size, so does head loss. The monitored extended period scenario displayed minimal variation in head supplied ranging from 25.63m pressure head to 27.48m pressure head throughout the 3-hour period. Comparatively, the re-sized extended period scenario showed considerable variation in head supplied ranging from 27.15m to 64.89m.

Further to the above, results show that the additional head loss experienced in pipes before the pump set decreased the available head at the suction side of pumps. This increases the head required to maintain the required pressure throughout the building. Indicating it may be beneficial to marginally increase pipe sizing as a means of reducing head loss throughout the cold-water supply upstream of the pump to decrease the system's pumping head.

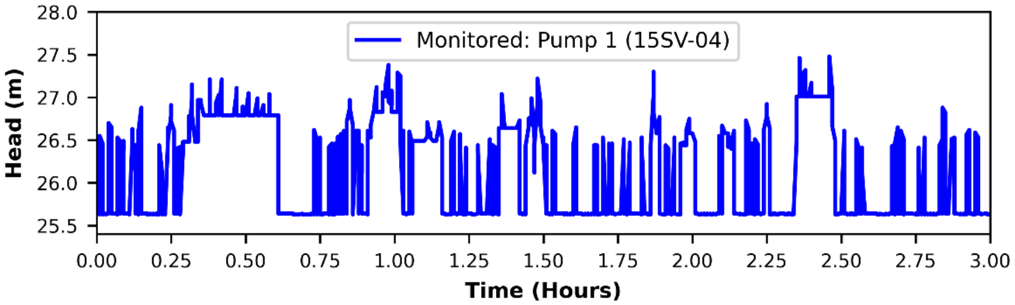


Figure 21 – Pump head supplied during the monitored extended period hydraulic modelling scenario

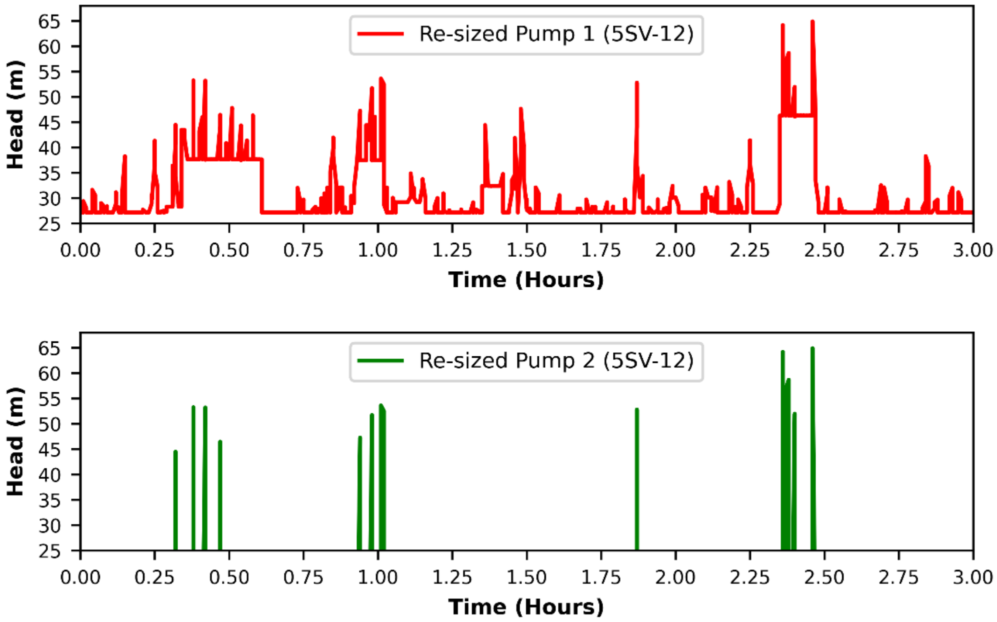


Figure 22 – Pump head supplied during the re-sized extended period hydraulic modelling scenario

Pump Efficiency

A review of pump operating efficiency is conducted for both the monitored and re-sized extended period modelling scenarios. Displayed in Figure 23 and Figure 24 is the flow supplied and operating efficiency for all pumps in operation during extended period modelling. Interestingly, the modelling conducted showed little improvement towards the average operating efficiency for the lead pump between monitored and re-sized scenarios. The monitored scenario average operating efficiency was 20.0% and the average for the re-sized scenario was 25.8%. This is a result of the constantly varied flow rates experienced within the building. Keeping in mind that the modelling scenario considers only a 3-hour peak period, where it is likely flow rates will lower for most of a day's typical water consumption outside this observation period. The secondary pump that was utilised during peak flows of the re-sized extended period scenario operated at an average efficiency of 64.9%.

These results demonstrate that giving consideration only 'no' or 'peak flows' can lead to inefficient pump operation. Whilst the advent of variable speed drive (VSD) pumps does offset the inefficiencies of a fixed speed pump set, results suggest pump system design could be further improved by developing a system that considers a more varied range of flow rates.

In the example of the system analysed, the average flow rate (demand) during the peak 3-hour period was 0.48L/s, suggesting it may be advantageous to implement a lead pump that is suited to operate at the average flow rate of a peak period and then implementing two further pumps to carry the remaining 2.44L/s of peak demand to improve overall pump operating efficiency.

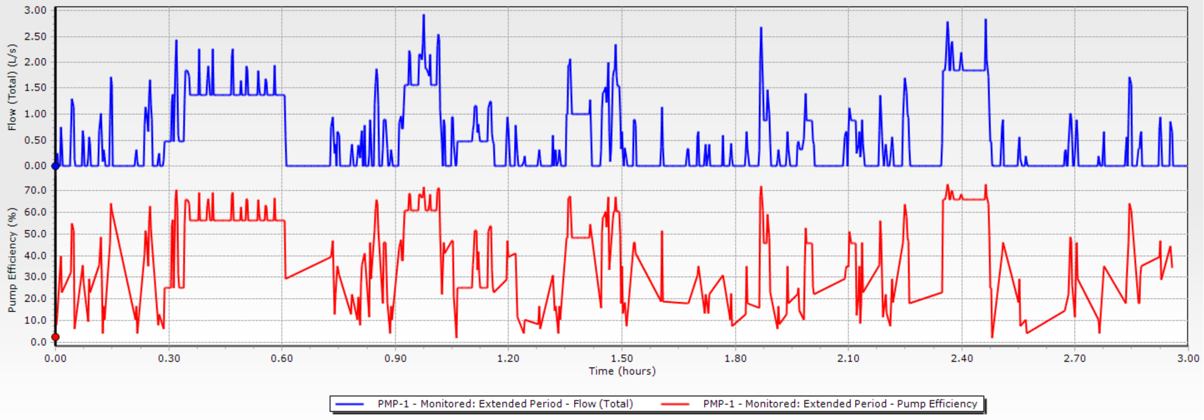


Figure 23 – Pump flow supplied and operating efficiency during monitored extended period hydraulic modelling scenario

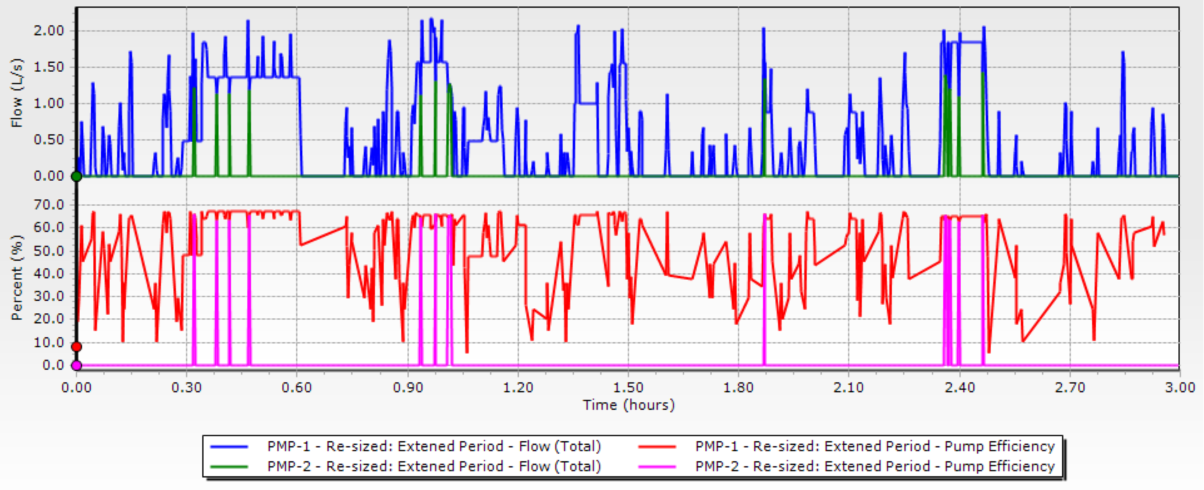


Figure 24 – Pump flow supplied and operating efficiency during re-sized extended period hydraulic modelling scenario

Plumbing Hardware

Plumbing hardware such as valves and water meters are components that are required to operate at a specific flow velocity ranges for optimal performance. For plumbing valves, operation at flow rates outside the specified manufactures range can contribute to poor control, noise, cavitation and premature wear (All Valve Industries Pty Ltd., 2015). From a designer's perspective, if it is believed low flows are present, a by-pass lines with appropriately sized valves for the altered hydraulic condition should be considered.

The measurement of water consumption through a customer water meter is most accurate over a specific range of observations. As an operational state moves outside this range, errors begin to accumulate that impairs the accuracy a customer water meter can track water consumption (Douglas et al., 2019).

Flow velocity values for extended period scenarios are evaluated to assess the suitability of the design of the PRV located in the main cold-water service.

Displayed in Figure 25 is a typical flow velocity observation for modelled PRV for (a) the monitored scenario, and (b) the re-sized scenario. For the monitored extended period scenario, the maximum PRV flow velocity was 0.38m/s. Due to the low demand, the operational velocities are always below the nominated flow velocity values of 1.0-2.0m/s (All

Valve Industries Pty Ltd., 2015). For the re-sized extended period scenario, the maximum flow velocity though the PRV was 2.32m/s. Whilst the re-sized scenario did observe flow rate velocities within the recommended range, because of the variances in demands observed, the modelled PRV only operates within the recommended velocity for 19.24% of observations over a 3-hour peak period. The results demonstrate that a narrow consideration of operational states such as ‘no flow’ or ‘peak flow’ in cold-water service design may lead to velocity based plumbing devices operating outside optimal observational ranges for a considerable amount of time within its lifecycle.

(a)

(b)

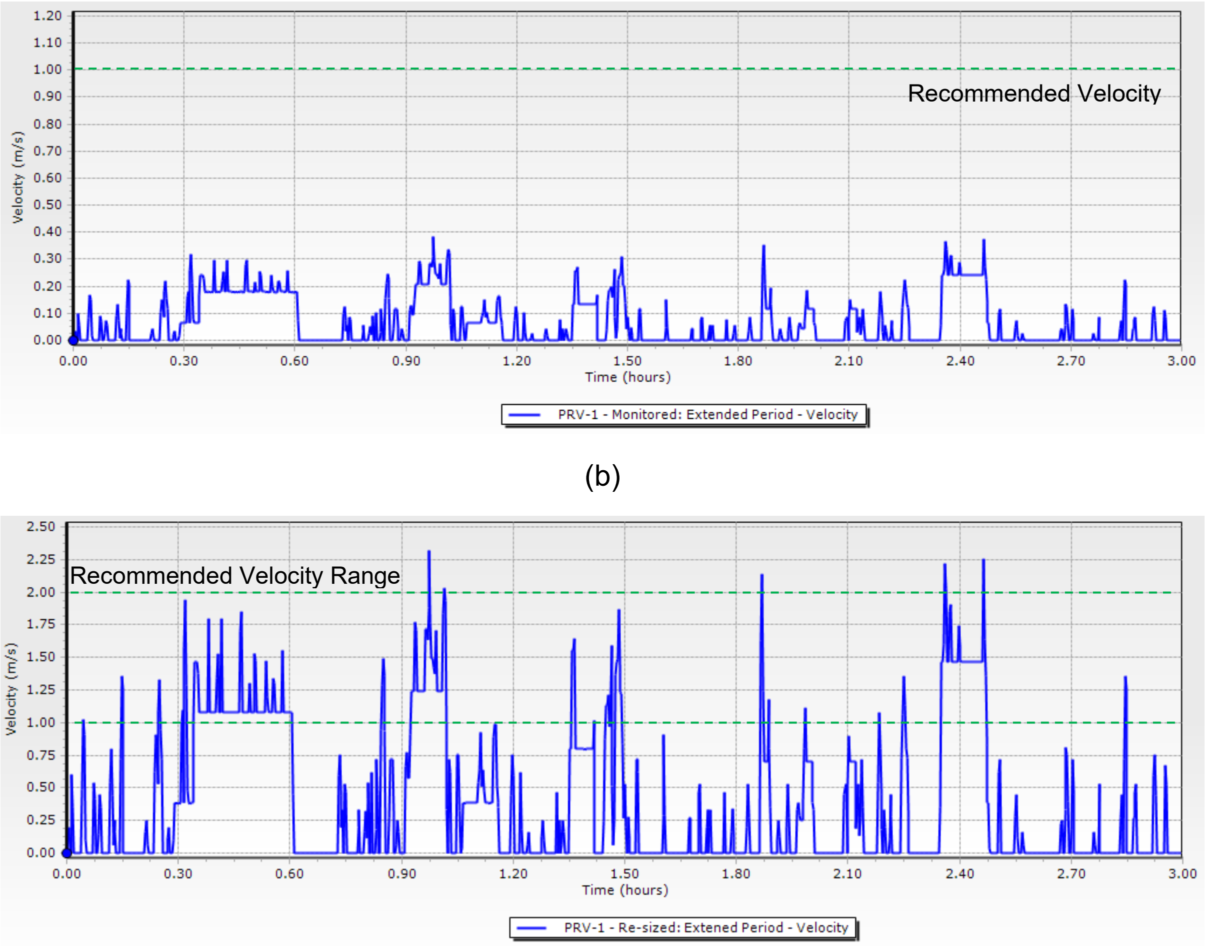


Figure 25 – PRV flow velocity observed in extended period hydraulic modelling

Summary of Results

Presented in Table 8 is a summary of hydraulic modelling results observed during all four scenarios.

Table 8 – Summary of hydraulic modelling results

Description	AS/NZS 3500.1: Single Period	Monitored: Single Period	Monitored: Extended Period	Resized: Extended Period
Peak flow rate	9.75L/s	2.92L/s	2.92L/s	2.92L/s
Maximum pipe flow velocity	1.28m/s	0.37m/s	1.14m/s	2.97m/s
Maximum pipe pressure loss	7.98kPa	3.52kPa	N/A	N/A
Pump BEP (flowrate : efficiency)	5L/s:75%	5L/s:75%	5L/s:75%	1.7L/s:67%
Pump relative speed	0.886	0.752	0.620[a]	0.650[a]
Pump efficiency	69.6%	66.2%	20.0%[a]	25.8%[a]
Maximum pump head supplied	30.3m head	27.5m head	27.5m head	64.9m head
Minimum pump head supplied	N/A	N/A	25.6m head	27.2m head
Maximum PRV flow velocity	1.28m/s	0.38m/s	1.28m/s	2.32m/s
Pipe size: Main Cold-water	DN100	DN100	DN100	DN40
Maximum flow: Riser A (demand)	9.75L/s	2.92L/s	2.92L/s	2.92L/s
Pipe flow velocity: Cold-water main	1.28m/s	0.38m/s	0.38m/s	2.92m/s
Pipe size: Riser A	DN65	DN65	DN65	DN25
Maximum flow: Riser A (demand)	1.59L/s	0.14L/s	0.87L/s	0.87L/s
Pipe flow velocity: Riser A	0.54m/s	0.05m/s	0.30m/s	2.10m/s
Pipe size: Riser B	DN80	DN80	DN80	DN32
Maximum flow: Riser B (demand)	3.72L/s	1.04L/s	1.58L/s	1.58L/s
Pipe flow velocity: Riser B	0.89L/s	0.25m/s	0.38m/s	2.34m/s
Pipe size: Riser C	DN80	DN80	DN80	DN32
Maximum flow: Riser B (demand)	4.44L/s	1.66L/s	1.66L/s	1.66L/s
Pipe flow velocity: Riser C	1.06m/s	0.40m/s	0.40m/s	2.46m/s

Notes

[a] Average values of the lead pump

DISCUSSION

Designed Demand VS Actual Demand

There is now significant evidence to support the hypothesis that many international plumbing codes and standards over-estimate peak flow rates in multi-level residential building due to the advent of water efficient fixture and appliances (Hobbs et al., 2019). Observation obtained from four Australian multi-level residential buildings as monitored in the current research has demonstrated that the designed peak demand using Australian plumbing design standards and practices can be significantly larger than the actual peak demand. The hydraulic modelling conducted provides much more information than the water demand at the cold-water inlet, and it has highlighted a gap between the plumbing industry's current understanding of assumed hydraulic conditions and the actual system performance. Because plumbing system design is strongly aligned with the designed peak demand (flow rate), over-estimated peak flow results in over-estimation in pipes, pumps and plumbing devices used to control pressure and flow. Knowing that plumbing system control devices such as pressure reducing valves or water meters require operation at a specific velocity range to ensure optimal function, the observed results demonstrate that these optimal velocities rarely occur.

Implication of Oversized Pipe Systems

Throughout industry it is widely accepted that the Hunter method does oversize modern-day plumbing systems with the perception that over-sizing offers additional comfort to the designer (AWWA, 2014). However, early studies suggest that cold-water plumbing systems designed using the current DtS method cost 10 to 20% more money to construct than those designed by the Verification Method (HCAA, 2019, Lucid Consulting Australia, 2019). Cold and heated water services consume energy to transport and heat water. Within Melbourne, Australia, the heating of residential water represents 27% of total energy demand (Kenway et al., 2014). Larger cold and heated water services cost more energy to operate, therefore, the systematic oversizing of plumbing systems results in a significant waste of energy.

Results obtained in the current study suggest the extent of oversizing and the implications it has to a plumbing system's performance are not fully appreciated during the design phase. The disparity between the design and the measured flow is considerable. Safety factors added in during the design phase increase system sizing further and results in very low flow velocities in pipes that unable to achieve self-cleaning. Pump systems operate at very low efficiency since they are designed to handle conditions that the plumbing network does not experience under normal operation.

Low flow rates associated with large pipe systems result in low head loss, and it may be an attractive attribute to a designer. However, plumbing equipment such as water meters and valves are designed to operate within a specific flow velocity range to ensure accuracy and correct function (Douglas et al., 2019). Limited or intermittent flow rates can cause valves to inconsistently operate and partially open, which can cause noise, vibration and pre-mature wear (All Valve Industries Pty Ltd., 2015). Entrained air is more prevalent in higher pressure, low velocity systems as the flow rate is insufficient to flush air out of the system (Bhatia, 2015b). The low flows experienced in buildings can also be a contributor to premature failures and water quality issues (Farooqi et al., 2009) seen in many plumbing systems. However, supporting evidence on these topics is limited and requires further investigation.

Implication of Downsizing

Although a reduced plumbing system size is commercially and environmentally attractive to building developers and designers, there can be risks and unexpected consequences. Results from the case study demonstrate a significant increase to pipe flow velocity and variances in hydraulics conditions experienced within the multi-level residential building considered. System losses also significantly increased with the smaller pipe diameters used. The energy required to pump water throughout a water service network is a function of system losses. This suggests designers will need to give a stronger consideration towards pumping systems to strike balance between initial capital cost associated to system construction versus lifecycle costs associated to energy consumption.

Roy et al. (2017) highlights that velocity-based events are a significant contributor to erosion-corrosion in copper pipes, although an optimal velocity is yet to be established for copper pipes and drinking water. These failure modes are already present in many of the currently over-sized systems.

Another key factor to consider is the impact and management of transient events (water hammer). Gong et al. (2013) highlights an increased magnitude of pressure waves for smaller pipe sizes due to the increased flow velocity and impedance when compared to larger pipes with the same flow change. In addition, research suggests specific consideration to transients in plumbing system design is forgone because of the complexity (Izquierdo and Iglesias, 2002) and additional financial outlay to procure software packages (Soriano et al., 2016). At present transient design validation is mandated only within the design of municipal water distribution systems and not the current versions of plumbing code of Australia.

Another implication of reduced system sizing is aligned with operational noise within cold-water service. It is likely designers will need to give further consideration to mitigate the audible by-product of velocity-based events aligned to high flows, valve operation and water hammer events.

RECOMMENDATIONS

The findings from this research indicate that there are major opportunities for the industry to provide the public a more sound and efficient plumbing design that will ultimately improve longevity and reduce lifecycle costs associated to both cold and heated water systems. Moving forward, it is recommended that the PCA and AS/NZS 3500 standards should be updated (modernised) to enable designers more accurately estimate peak hydraulic demands and optimally size the pipes, pumps and other flow control devices for various types of buildings. Future design should also consider whole plumbing system performance under various states of flows (in addition to the peak flow).

Modifications in plumbing design standards need to be supported by scientific evidence, which can only come from proper scientific research. The development of IAPMO’s WDC are backed by years of research in the US (Buchberger et al., 2017, Omaghomi et al., 2020). In Australia, plumbing design has not been a focus of research since 1970s. Governments will need to play a significantly role in funding and coordinating research, since the Australian plumbing industry is comprised of small businesses and lack of research capacity.

The following work will contribute to the modernisation of the plumbing standards and codes:

Water Demand and Pressure Monitoring for Various Types of Buildings

The current study captures the cold-water demand of four multi-level residential apartments buildings. Whilst the findings have confirmed the current Australian cold-water service standard AS/NZS 3500.1 overestimates peak flow rates in residential buildings, it is a narrow snapshot of the many building types the PCA and AS/NZS3500.1 are applied to.

Future work should focus on collecting additional water consumption data across all Australian states for both water services (heated and cold) and for various types of buildings to gain a clear understanding of the actual water consumption patterns in each specific building type. Suggested building types are, but not limited to:

- Multi-level Residential Buildings, with varied apartment quantities
- Hospitals
- Aged Care
- Offices
- Schools
- Commercial Buildings

Real data are essential to enable the development of the ‘probability of usage’ values when applied to the VM or any probabilistic method used to predict peak flow rates. Both the cumulative water demand (for the whole building) and the fixture water uses (on the household level) are important information to collect.

Several residential end-use use studies (REUS) have been conducted throughout Australia and New Zealand between 2000-2014 in many major water utility networks to better understand fixture end-user behaviours in single or detached residential dwellings (Beal and Stewart, 2011, Arbon et al., 2014, Heinrich, 2008). Work conducted to develop the IAPMO’s WDC used data obtained from US based REUS to evaluate fixture end-user behaviour. A similar approach could be adopted to create probability of usage values for each fixture that is specific to the Australian climate. However, research is needed to determine the most appropriate sampling rate (temporal resolution) to capture and define the “peak” flow.

Pressure monitoring can be undertaken together with the flow monitoring to add value to the effort. The transient pressure (water hammer) is the focus and it requires high-speed sampling (200 samples per second or more). The measured pressure data will be essential for the hydraulic transient analysis as discussed in a later section.

Extended Period Hydraulic Modelling

Extended-period hydraulic modelling can provide a full picture of the various steady-state hydraulic conditions that would be experienced across the network at different time. This modelling practice has been standard in the design of municipal water distribution systems (Walski et al., 2001) for decades; however, plumbing system design is still largely based on simple calculations of the peak flow condition similar to the worked examples shown in plumbing design guides (Smith, 1976, International Copper Association Australia, 2015, International Copper Association Australia, 2021).

The hydraulic modelling conducted in this research presents an overview of the hydraulic condition experienced in a specific residential building for a single 3-hour morning peak period. To build on the work conducted, hydraulic modelling should consider longer periods ranging from days to weeks, with modelled water services subjected to varied hydraulic patterns to improve industry’s knowledge base of the hydraulic conditions experienced in residential buildings.

Water can have a long contact time with premise plumbing systems in complex buildings. This long ‘water age’ can lead to low disinfectant residuals, and consequently the growth of biofilms and the formation of disinfectant by-products (National Research Council, 2006). Extended-period hydraulic modelling will help to understand the flow velocity and the water age, which are important factors to water quality. Numerical modelling can also reveal lifecycle performance such as pump operating efficiency, which enables the optimisation of the water service design and energy consumption.

Hydraulic Transient Analysis

Currently there is limited research regarding hydraulic transients (water hammer, unsteady flow) in plumbing systems, although it is known to the industry that water hammer needs to be controlled to avoid the noise issue (Yerges, 1985). With many fast-operating flow control devices (e.g. solenoid valves) in a plumbing system, additional considerations to system performance outside the ‘steady-state’ condition should be given to provide insight towards the behaviour and magnitude of transient events in both current and future system designs to ensure safe operation and reduce premature failures of plumbing hardware and devices.

Resent research conducted in municipal water distribution systems demonstrate that the operation of premise plumbing systems can be a source of transients that negatively impact the city pipeline network (Stephens et al., 2017). Experimental studies by Lee et al. (2012) demonstrate that hydraulic transients generated by water usages in a house can induce negative pressures, which impose risk to pipe integrity and water quality. Hydraulic transient analysis will become more important for future plumbing systems with reduced pipe sizes and increased flow velocities, which enhance hydraulic transients for the same water operation.

Review Existing Issues related to Premise Water Services in Australia

Reviewing and understanding existing issues in cold and heated water services can help to identify not only problems associated with current practices, but also potential issues in future systems with reduced pipe size and increase velocity. While many issues may be related to construction or operation rather than the design guidelines, good design standards would anticipate the common issues and promote preventative measures.

Plumbing defects can cause significant consequences. In 2008, a burst pipe in the Balencea apartment building in Melbourne, VIC, flooded four floors causing over $100,000 damage to the partially constructed building (Herald Sun, 2008). The commissioning of the Children’s and Women’s Hospital in Perth was delayed for years due to widespread corrosion of plumbing systems and the presence of heavy metal in the water (Government of Western Austalia, 2017). In June 2019, hundreds were evacuated and forced to find alternate accommodation due to an apartment water leak in Melbourne VIC, central business district (Koob, 2019). In July 2019, during the testing and commissioning process, a major pipe burst occurred on the ninth floor of the Verve building located in Newcastle, NSW (McKinney, 2019).

Plumbing defects are not restricted to early constructions. A survey conducted for assessing the effectiveness of strata management found that 42% of the common defects were associated to internal water damage and 22% were listed as defective plumbing (Easthope et al., 2012). A report published by Chubb Insurance has shown that the average cost of a water damage claim has risen by 72% between 2014 and 2018 with burst flexible hoses that connect to sinks or washing machine being the leading cause of water damage (Chubb, 2019).

Presently, there is little published research pertaining to the causes of water service defects and failures. It is recommended that a systematic review of known issues be compiled and where possible, investigated to widen industry's understanding of specific design and construction scenarios that lead to premature failures of the water service.

CONCLUSIONS

Observed water consumption data in four specific multi-residential apartment building has been compared against the designed flow from Australian plumbing standard AS/NZS 3500.1, comparable international plumbing codes and future methods for predicting peak flow rates. Results demonstrate the current Australian plumbing standard significantly overestimates peak flow rates by a range of 217-326%. All other methods compared predict peak flow rates considerably lower than the Australian standard AS/NZS 3500.1, providing further evidence to support the finding that current Australian design guideline for peak flow estimation is outdated.

In addition to the evaluation of peak flow rates, an evaluation of the range of flow rates experienced in multi-residential building has been conducted. Flow rate values observed demonstrates that buildings are rarely subjected to peak flow rates (only observed over one observation period), while lower flows dominate the hydraulics conditions experienced in residential buildings. This demonstrates that designing with a bias toward 'no' or 'peak' flow promotes a narrow view of the hydraulic conditions experienced in buildings.

Hydraulic modelling for the HCAA's Waterloo building cold-water service has been conducted for several single-period and extended-period flow scenarios under the assumed design (AS/NZS 3500.1), the monitored and the re-sized plumbing conditions. The results of the modelling have identified a large gap between the assumed design stipulated by AS/NZS 3500.1 and the monitored scenario validated through flow rate measurements observed during the HCAA's water demand investigation. Hydraulic modelling conducted has identified wide-spread low-flow velocities for the monitored scenarios, confirming the current system is oversized and performing outside the assumed design conditions.

The plumbing system was downsized to form the "re-sized scenario", where the largest pipe size was reduced from DN100 to DN40 whilst still maintaining compliant operating conditions set within the Australian plumbing standard AS/NZS 3500.1. As a result of a re-sized system, pump operating efficiency was marginally improved by sizing the pump system to optimally perform at peak flow rates only. Further pump efficiency gains could be achieved by implementing varied pump sizes to accommodate lower demands that dominate observed flow rates when considering typical residential multi-level residential apartment building cold-water consumption. However, downsizing can result in many complications which have not been fully investigated in this research.

Further research is needed to enable the update of the Australian plumbing code and standards. Four areas of focus are recommended, and they are: 1) water demand and pressure monitoring for various types of buildings; 2) extended period hydraulic modelling; 3) hydraulic transient analysis; and 4) reviewing existing issues related to water services in Australia.

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APPENDIX – Pump Performance Curves

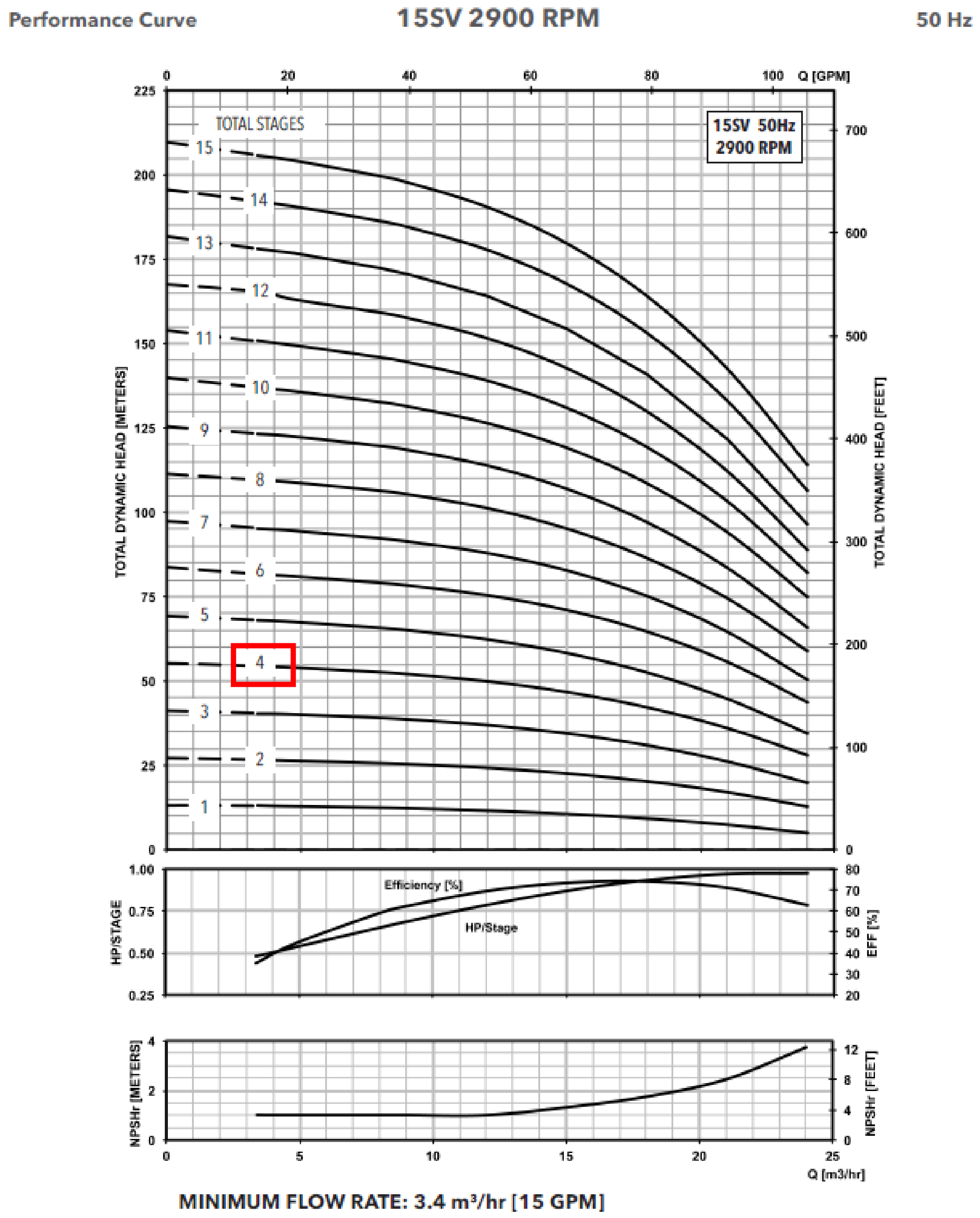

Figure 26 – Pump performance curve, as built state