Residential water demand modelling and hydraulic reliability in design of building water supply systems: a review
R. D. Mangalekar and K. S. Gumaste

ABSTRACT
The building water supply system is a fundamental unit in water supply systems as it is directly associated with end users. However, the studies available on its efficient design are limited. Water demand estimation continues to be an important issue in water supply systems’ design because of its multifaceted nature. Hunter’s curve, or Fixture Unit method, is widely used for estimating the load on plumbing. Regardless of its popularity, it has a few drawbacks and is arbitrarily modified in some plumbing codes. Fixture-use probability, a basic entity in the Fixture Unit and some other methods, is a difficult parameter to estimate. Commonly, high-resolution field data is used for stochastic modelling of residential water demand which may not be always available. The paper reviews important residential water demand models in view of their applicability in building water supply system design. The irregular nature of water demand in buildings is due to uncertainty in water-use behaviour of users at fixture level. Use of soft-computing techniques can provide an advantage over the other methods in modelling such behaviour. The paper also discusses reliability of building water supply systems and applicability of some common indices for estimating reliability of building water supply systems.

Key words | building water supply system, Hunter’s curve, hydraulic reliability, pipe sizing, plumbing, residential water demand

HIGHLIGHTS
• Mostly, residential water demand models use high-resolution field data.
• Fixture use probability is obscure and difficult to estimate.
• Estimation of hydraulic reliability of building water supply systems is required.
• Accurate estimation of water demand is neither possible nor required in the design.
• Estimation of water demand and hydraulic reliability are interdependent but complimentary aspects for efficient design.

INTRODUCTION
Water distribution system (WDS) is a term used to represent a system of collection, storage and transportation of water from treatment plant to the point of house service connection. Beyond the municipal water meter, water is carried to end users by the plumbing system, herein referred to as the building water supply system (BWSS) (Gad & Abd-Elaal 2015). Some basic input parameters required for design of both the above hydraulic systems are common, like pipe layout, nodal demands, nodal elevations, head at source and residual head at nodes, etc. Analysis and
design of WDS is characterized by water demand estimation and subsequent demand allocation to nodes. Variation in water demand at a node in WDS may be moderate due to the large population served by the respective node. On the contrary, in the BWSS, the demand at water supply fixtures is intermittent and quite uncertain as it is directly affected by consumers. Water demand at different household fixtures is dependent on user habits, and a number of demographic and socio-demographic characteristics (Blokker et al. 2010; Willis et al. 2013; Beal & Stewart 2014). Thus, in spite of physical similarity, principles governing the design of BWSS are different to those of WDS.

Pipe sizing in BWSS is conventionally based on the principle of simultaneous demand. The probability of using certain number of fixtures simultaneously is considered in the calculation of maximum flow through a pipe supplying water to these fixtures. Fixture-use probability ($p$) is a basic entity used to calculate probable maximum simultaneous demand (PMSD) as a design flow through a pipe in BWSS, assigning the probability distribution for the number of fixtures being used simultaneously (Hunter 1940; Murakawa 1985). The estimation of load on the plumbing system of a building in terms of water demand is a critical step after which the hydraulic analysis is performed to ensure the minimum residual head at user end (Cole 2011).

Majority of the National and International Codes utilize Hunter’s curve (1940) for pipe sizing in plumbing, using the concept of Fixture Units. Because of the sound probabilistic approach and easy calculations of PMSD, Hunter’s Fixture Unit method is popularly used in plumbing system design. However, it is an extensively accepted fact that Hunter’s curve overestimates water demand in plumbing pipe sizing (Murakawa 1985; AWWA 2004; Mazumdar et al. 2014). Apart from this, some other issues associated with the Fixture Unit method are highlighted in the paper.

There are a number of models and methods proposed by various researchers for estimating residential water demand. For BWSS design, end-use models can be effective as they study water use events at fixtures (Blokker et al. 2010). Often, such stochastic end-use water demand models require a huge amount of high-resolution field data, which may not be always available for every region or locality, especially in developing countries. Some of the models and methods in literature are effective in estimating the instantaneous residential water demand (Hunter 1940; Wiston 1994; Omaghomi 2019), but they are based on $p$-values. Obtaining the $p$-values of fixtures might be a difficult and extensive task. Nevertheless, residential water use habits change over time and location. This change in water-use behaviour needs to be considered by a timely update on values of fixture-use probability ($p$), to be used in the water demand models for BWSS pipe sizing in the respective locality.

Water demand pulse models use probability distribution for fitting the data of arrival of the water demand pulse (Buchberger & Wu 1995; Alvisi et al. 2003; Alcocer-Yamanaka et al. 2012; Di Palma et al. 2014; Di Palma et al. 2017). Scrupulous statistical analysis is required to develop such models from the field data.

As water demand is a subjective event, its deterministic models are difficult to build and might involve incomprehensible parameters. Soft-computing, or Grey-box approaches, have been used by some researchers to overcome this problem (Bhave & Gupta 2004; Tabesh & Dini 2009; Bennett et al. 2013; Oliveira et al. 2013; Vijayalaksmi & Babu 2015). Also, accurate estimation of water demand is practically unattainable due to several factors affecting the event. With the use of soft-computing techniques such as fuzzy logic, subjective behaviour of users can also be modelled mathematically to estimate water demand (Oliveira et al. 2013). Such models can include user characteristics along with the other demographic and climatic factors affecting water demand.

Reliability studies on the water supply system (WSS) are required to be done to ensure its functioning under abnormal conditions of operations. Majorly, estimation of reliability of WSS consists of two aspects, viz. evaluating possibility of failure of its components and calculating the degree of demand dissatisfaction at nodes during infrequent operating conditions. Latterly referred to as hydraulic failure, is the inability of the WSS to satisfy the required quantity of water with a specified head during periods of high demand. Hydraulic failure may occur due to inadequate design of components, changes in demand over a period of time and reduction in heads available at nodes due to increased roughness of pipes (Bao & Mays 1990). As hydraulic reliability (HR) quantifies demand satisfaction at nodes, estimation of water demand is crucial for a reliability analysis.

Hydraulic reliability of WDS has been widely researched (Bao & Mays 1990; Fujiwara & de Silva 1990;
Very few studies have focused on investigating the reliability of BWSS (Gad & Abd-Elaal 2015; Abd-Elaal & Gad 2018). Consideration to hydraulic reliability can help strengthen the design process by assessing the performance of BWSS for varying operating conditions like high and low demands. The reliability measurement indices like entropy, resilience index etc. can be used for estimating HR of BWSS after certain modifications in their formulation. Also, it is important to consider the head at nodes and source in reliability calculations for BWSS as its design is necessarily based on head-dependent analysis (HDA).

The improper design of BWSS may lead to inefficient use of water, compromise with the quality of water reaching the user, large maintenance costs and waste of energy too. With the growing concern about sustainability and water management, improving BWSS design is inevitable.

All the above aspects call for an investigation into the design of BWSS with emphasis on water demand modelling and due consideration to estimating its HR for effective urban water management and sustainable development. The important water demand modelling approaches for residential water use, including the commonly used Fixture Unit method, are briefly discussed in this paper. Hydraulic reliability and its indices to estimate reliability of BWSS are also discussed.

MODELLING RESIDENTIAL WATER DEMAND

Water demand in residential buildings is a quite probabilistic yet important variable in BWSS pipe sizing. Estimation of water demand is difficult because of the number of factors affecting water demand and the dynamic nature of the variable itself. The uncertainty in water demand at various common fixtures in residential buildings causes a great deal of complexity in appropriate pipe sizing. Being on the conservative side in estimating demand might not only affect the economy of the design, but can also be a great threat to the quality of water reaching consumer ends due to increased residence time of water in the system causing growth of harmful micro-organisms like Legionella. The interaction between user and water fixture and the study of simultaneous use of fixtures is important in the pipe sizing in BWSS.

Various methods and models are available in literature for the estimation of residential water demand, as discussed in this section. Some of the methods are used by the standards and codes (e.g. the Fixture Unit method, Loading Unit method) while the other models are not so popular among plumbing designers and practitioners (e.g. pulse models, end-use models).

Fixture Unit method and related issues

Hunter (1940) introduced the concept of Fixture Units to estimate demand in BWSS using a methodical probabilistic approach. Using the idea of Fixture Units, Hunter was able to present combined effects of different types of fixtures on a flow through a pipe serving them. The curve of demand in gallons per minute (gpm) against Fixture Units was developed (Figure 1). The Hunter’s curve can be easily used for estimating PMSD for BWSS pipe sizing.

Hunter applied binomial probability distribution for number of fixtures operating simultaneously in BWSS. Fixture-use probability \( p \) was used considering the operating condition of a fixture as On or Off. It was calculated as a ratio of duration of use of a fixture \( (t) \) and average time interval between its two consecutive uses \( (T) \). A failure rate of 1% was considered while calculating PMSD; that is, a confidence limit (CL) of 99%. The assumption of ‘congested

![Figure 1](http://iwaponline.com/ws/article-pdf/21/4/1385/903234/ws021041385.pdf)

No. 2: Flush Tank

No. 1: Flush Valve
use’ was made implying continuous use of a particular fixture during the period of peak demand. Demand curves for three fixture types, namely water closet with flush valves, water closet with flush tanks and bath tubs were developed. For the combined effect of different types of fixtures served by a given pipe, an arbitrary scale of 1 to 10 was used for assigning the weights to different fixtures. These weights are called Water Supply Fixture Units (WSFU), which are determined by noting the ratio of numbers of given types of fixtures corresponding to a given value of flow.

The concept of Fixture Units was well established to regularize pipe sizing in BWSS. The only quantities required for pipe sizing using the Hunter’s Fixture Units approach are number of fixtures (n), fixture flow (q) and probability of use (p) of each type of fixture. Though Hunter’s Fixture Unit method is quite convenient for pipe sizing, it was based on the water-use practices observed around 80 years back. There has been considerable change in water-use habits over this period of time. The change in water use may be attributed to changes in lifestyle, climate and technology advancement. Water-efficient fixtures are more common nowadays. Fixture-use characteristics (t and T) of new efficient fixture types being used in buildings need to be estimated for adopting the Hunter’s Fixture Unit method for the sizing of pipes serving these fixtures.

Hunter assumed continuous use of fixtures during peak period for estimating PMSD. It seems highly unlikely for water fixtures to be continuously occupied by users in a residential building. Adding to the conservative design criteria, Hunter used CL of 99%. The use of Hunter’s Fixture Unit method without consideration to these aspects has been found to overestimate the water demand in BWSS and consequently oversizing of pipes. With this regard, the modification of Hunter’s curve was presented by Mazumdar et al. (2014). According to Mazumdar et al. (2014), Hunter’s method can still be used but it needs updating the values of CL, fixture flow rates (q) and fixture-use probability (p). PMSD was estimated by considering then-available fixture flow rates, reduced p values and by approximately reduced CLs from 99% to 95, 90 and 85%. Substantial water saving was observed through theoretical calculations but their study was not validated for actual pipe sizing in buildings.

For sizing of pipes in BWSS, the values of WSFU for different fixtures are provided by Plumbing Codes. It is observed that the values of WSFU for a given fixture type vary across different Codes; for example, for water closet with flushometer tank, values of WSFU given by the International Plumbing Code (IPC 2018), National Standard Plumbing Code (NSPC 2009) and Uniform Illustrated Plumbing Code (UIPC India 2018) are 2, 2.5 and 3 respectively, for private occupancy. Even though the difference in the adopted values of WFSU by different codes seems minor, PMSD calculations using these codes might be affected for a building with large number of fixtures. Nevertheless, the adequate explanation of adopting particular Fixture Unit values is also found to be unavailable in the codes.

Determination of the fixture-use probability (p) in the Fixture Unit method is an elusive and tedious part. It requires values of t and T obtained from a large amount of high-resolution field measurements. Omaghomi (2019) estimated the Fixture-use probability values for efficient fixtures using high-resolution data collected by Aquacraft Inc. from around 1,000 households in the USA between the period of 1996 to 2011. The peak hours of water use at observed households were identified and used for calculation of p values.

Factors affecting water demand such as demography, climate, culture and lifestyle are functions of geographic location. Moreover, water use at a fixture is a function of age, occupation, income, family composition, occupancy at home and so on (Blokker et al. 2010; Willis et al. 2013; Beal & Stewart 2014). Variation in these factors may lead to change in the values of parameters – t and T, which are utilized to find probability of fixture use (p). Cole (2011) presented a brief discussion on the frequency of fixture use (T), specifically for toilets, and stated T as a most difficult parameter to arrive at in the Fixture Unit method. Earlier, Breese (2001) had also pointed out the uncertainty associated with the value of T. Thus, the value of T is highly unpredictable in this matter and can have a substantial effect on the estimated design flow. As WSFUs are conventionally based on p values, it is conclusive that WSFU values cannot be universal and need to be established locally for respective regions attributing to the factors like geographic location, socio-demographic characteristics and water-use habits of users etc. Demarcation of an area over which
these values remain constant is the subsequent important investigation to be looked at.

The ease of use and conservative design resulted in the popularity of Hunter’s curve and Fixture Unit method for plumbing design. With the growing concern about sustainability, conservative design is less likely to be acceptable. Along with arbitrary modification of Fixture Units, some codes try to cater to the overestimation of Hunter’s curve by applying approximate factors in the design. For example, UIPC of India (2018) suggests use of 75% of demand load on the service pipe to estimate the design flow in a branch, which tees off from respective main or service pipe. While the codes suggest such approximations for efficient design, some designers arbitrarily modify the values obtained from the codes based on their own experiences.

**Standard practices succeeding Hunter’s method**

A number of Standard Codes across the world are based upon the Hunter’s Fixture Unit method. Following Hunter’s milestone work, attempts were made to develop new methods of demand estimation for pipe sizing in BWSS. Some of these methods adopted by some codes follow an approach similar to that of Hunter’s (e.g. the Loading Unit method), while some other are based on an empirical relationship between the number of fixtures and design flow.

The Queuing theory was used for estimating the number of simultaneously used fixtures by Murakawa (1983). The probability distribution for simultaneous use of fixtures was approximated to Poisson’s distribution in place of the binomial distribution used by Hunter. Murakawa’s ‘Loading Units’ were found to produce lower design flow rates than that of Hunter’s curve. Murakawa’s work was later adopted in the Japanese code on plumbing design.

The codes in Scandinavian countries follow a deterministic model given by Rydberg in 1945 (Konen & Goncalves 1993). The probability of fixture-use, fixture flow rate of each fixture and the failure factor were considered for estimating design flow by Rydberg. Further, Codes of Practice in the UK are based on the Loading Unit method by Howick (1964) who adapted Hunter’s method (Ingle et al. 2014; Hobbs et al. 2019). British and European standard codes BS6700:2006 and BS EN 806-3:2006 use Loading Unit values to determine the PMSD and size the pipes in BWSS. The Plumbing Codes of other countries like Germany (DIN1998-300), France (DTU 60.11), Portugal and Brazil (NBR 5606) use a deterministic approach for estimating the design flow for pipe sizing (Wong & Mui 2018).

The American Water Works Association (AWWA 2004) presented the Fixture Value method, recognizing that the Hunter’s curve overestimated the demand in buildings. Fixture Values were obtained for every different type of fixture by noting its absolute maximum flow when operated without combination with other fixture types at 60 psi. This method of pipe sizing is purely based on the observations of water use data in different building types.

With the aim of developing a new tool for pipe sizing in buildings, appreciable efforts have been taken by Omaghomi & Buchberger (2014). Two approaches to estimate peak water demand in residential buildings, namely Exhaustive Enumeration (EE) and Monte-Carlo simulation method were used to develop a dimensionless curve to determine peak flow for any number and type of fixtures. Recently, Omaghomi & Buchberger (2018) developed the Water Demand Calculator (WDC), which is available on International Association of Plumbing and Mechanical Officials’ website (IAPMO) and seems quite a prominent tool for pipe sizing in plumbing. It selects the suitable method for peak demand estimation from Exhaustive Enumeration (EE), Zero Truncated Poisson-Binomial Distribution (ZTPBD) and normal approximation of Poisson-Binomial distribution (NAPBD), based on the building size (n) and average probability of fixture use (p). The fixture use probability values used were developed from a large amount of high-resolution data on water use in domestic households collected over a period of around 15 years in the USA. WDC can be an effective and handy tool for BWSS pipe sizing, but the values of the basic parameter p need periodic updating and a new set of values need to be established for every different region or locality under consideration. Moreover, the relation between the user and the fixtures, which is important to be understood for residential demand modelling, was not explored in the study.

Apart from the methods adopted by Codes and Standards, methods proposed by researchers to estimate residential water demand still need some simplification for using them in BWSS pipe sizing. Some important types of models are discussed in the further sub-sections.
Demand pulse models

A time series of water demand can be represented in the form of a series of pulses characterized by intensity, duration and frequency of water use event. In deterministic modelling, these demand characteristics are computed and in case of stochastic modelling, they need to be estimated by fitting data into appropriate probability distributions. For spatial and temporal variability of indoor residential water demand, Buchberger & Wu (1995) developed a stochastic model with the help of Queuing Theory. Occurrence of residential water demand was assumed to follow a non-homogenous Poisson rectangular-pulse (PRP) process. The model was characterized by mean, variance and probability distribution of a flow rate. The determination of the parameters of a PRP model requires high-resolution field data on household water use. Further, a program for obtaining stochastic and deterministic water demand in residential buildings, PRPsym, was developed by Buchberger & Li (2007). PRPsym can be used to generate water demand pulses at any time scale from 1 second to 1 day for any number of nodes in the WDS as well as for any fixture. Apart from using costly field measurements, the PRP model fails to recognize the effect of user characteristics and other factors affecting water demand on the pulse generation.

Another type of rectangular pulse model, Neyman-Scott Rectangular Pulse (NSRP) (Alvisi et al. 2003; Alcocer-Yamanaka et al. 2012), consider the water use event at a fixture as an elementary demand (ED) and at a group of fixtures being operated simultaneously as demand block (DB). The time series of residential water use events in NSRP was obtained by adding ED at every instance of time. The arrival of DB and ED was represented by means of Poisson’s process. The field observations at different spatial and temporal scales are necessary for parameterization of these models.

A noteworthy study on residential water demand at an end-use level was done by Blokker et al. (2010). The residential water demand was modeled into a very simple stochastic time-series model SIMDEUM (SIMulation of Residential water Demand: an End Use Model) using the statistical information on users and fixtures in a domestic household. The number of persons in a household, their age, family composition, penetration rate of fixtures in households, duration and frequency of use, end uses and flow through each fixture were some of the parameters used. The SIMDEUM model builds the instances of use of fixtures from probability density function (PDF) of water use events derived from the diurnal activities of individuals. This end-use model can be built without the help of field measurements, but requires large amount of statistical data on users and fixtures. The efficacy of SIMDEUM, if used for BWSS pipe sizing, may be affected by fitting of data on water-use characteristics (frequency, duration etc.) of fixtures into appropriate distribution.

An overall pulse (OP) model for residential water demand estimation also uses the field measurements to estimate the water demand of a cluster of users or households (Di Palma et al. 2014; Di Palma et al. 2017). The frequency of cluster arrival was represented as a Bernoulli’s distribution, while its duration and intensity were found to fit into exponential distribution from the experimental data. These time series or rectangular pulse models need to be processed further in order to determine PMSD, if used for pipe sizing in BWSS.

In a comparative study of models for generating household water demand pulses, Creaco et al. (2017) considered two types of models. The first type of models considered were ones which generated water demand at household level. These models considered the stochastic nature of water demand and included PRP, Neymar-Scott Cluster (NSC) and Bartlett-Lewis Cluster (BLC). The second type of models considered were those generating water demand at fixture level. SIMDEUM was the only model used from this category. At single household scale, SIMDEUM was found to perform better in producing maximum flow rate at 1-second and 1-min scale.

It is important to note that the number and type of fixtures served by different pipes in BWSS vary as per building planning, pipe layout and size of building. Thus, use of an end-use model for design of BWSS would be effective as compared to models generating water demand at household level. Such end-use models are discussed in the next sub-section.

End-use models

In BWSS, the study of demand at each fixture facilitates modelling of water demand for pipe sizing effectively as the flow of water in a pipe is directly associated with use of fixtures served by it. End-use models require detailed
information on water use at each fixture type by users in the households. The relation between users and different water consuming appliances can be understood through such models.

A GIS based end-use residential water demand models were developed by Gato (2006) for estimating daily water demand in the urban area of Melbourne. The end-use models for the household fixtures were based on the disaggregated data from the data loggers at individual households. The tedious and heuristic process of disaggregation of water use data at household level into the different end uses may reduce the efficiency of such water demand models.

SIMDEUM (Blokker et al. 2010) is one of the important end-use models which considers some user characteristics (age, gender and occupation) and diurnal pattern of user for modelling residential water demand. With the help of Monte-Carlo simulation, a number of possible water demand patterns were generated for a given household or number of households using the statistical data on users, water use activities and fixtures.

The significance of the end-use study is not limited to the design of BWSS but can be extended to integrated urban water management (IUWM). The multi-scale end-use model proposed by Rathnayaka et al. (2017) predicts the water demand at different temporal (hourly to annually) and spatial scales (individual house to suburb). The concept of user groups used to represent the variation in water use habits underlines the user’s significance in water demand modelling. The stochastic models were developed to predict the end-use water demand at fixture level for each user group.

End-use studies are detailed investigations on the occurrence of a water use event at a fixture. User is a prime factor in such models. In a more inclusive study on water demand modelling, Ferreira & Goncalves (2019) presented a stochastic simulation model for estimating residential water demand in a view of BWSS components’ design. Deterministic variables like number of floors and number of flats in a building as well as random variables such as population groups, type of work of users, times of different activities of users in the house, and so on, were considered. For any fixture, probability of instance of use was calculated from the ratio of the average volume of water used to total average volume of water used in a day. The design flow obtained was around 61% of a flow obtained using the Brazilian standard. Such study is representative of the significance of user characteristics and local water use habits in residential water demand modelling for BWSS design.

**Soft-computing techniques and some simple mathematical models**

Amongst the different approaches of water demand modelling, the use of soft computing techniques such as fuzzy logic (FL) and artificial neural network (ANN) are being more commonly researched because of their capacity to resolve the complex nature of the problem. A water use event is inherently uncertain in its occurrence, intensity and duration of use. Such uncertainty and non-linearity in the model parameters and their inter-relation respectively can be addressed through use of FL.

Bhave & Gupta (2004) used trapezoidal membership function (MF) for the fuzzy nodal demands and nodal heads in water distribution network (WDN) design. Tabesh & Dini (2009) developed and compared around 50 fuzzy and neuro-fuzzy models with different combinations of input variables for forecasting hourly and daily water demand using the meteorological data as input.

The user’s perspective on using sanitary appliances was considered through fuzzy logic reasoning by Oliveira et al. (2013) for estimating residential water demand in a sub-metered building. Duration of use of shower was estimated from subjective information provided by family members of the study house. Duration and instance of use of other fixtures were determined by three-point method assuming Gamma distribution and Monte-Carlo simulation respectively. Fuzzy logic was used only for estimating duration of shower use with temperature of surrounding and instance of use as inputs. The design flow rate obtained was found to be 23% less than the deterministic model in the Brazilian standard.

In another study, an ANN based end-use model by Bennett et al. (2013), used a large amount of socio-economic and demographic data from the South-East Queensland Residential End-use Study (SEQREUS) of 250 households to forecast water demand by each fixture and total indoor demand. Critical variable factors affecting indoor Residential water demand were presented as input for the ANN forecasting model for each end use.
Vijayalaksmi & Babu (2015) used an adaptive neuro fuzzy inference system (ANFIS) with different MFs to predict the water demand. ANFIS combines the advantages of fuzzy modelling and neural network’s black-box approach to model the relation between the input and output for further prediction of the unknown. The available daily water use data were used to model the domestic water demand prediction. Selection of type and number of MF is a backbone of such models, which will affect the performance of the model. Moreover, the masking effect has to be addressed when the number of parameters used in the model have different ranges of values (Suh & Ham 2016). A combination of ANN with data processing techniques is illustrated for modelling water demand by Altunkaynak & Nigussie (2017).

The new methods and models of demand estimation proposed by researchers are not easily adopted by the designers and practitioners due to their lack of confidence in the proposed method (Ingle et al. 2014; Hobbs et al. 2019). Also, most of such models are not in easy-to-use form and need further simplification when used in actual practice. Some of the simple probabilistic models, which give the direct value of design flow, can be advantageous for design practices in this matter.

Webster (1972) (Konen & Goncalves 1995) and Wistort (1994) provided simple mathematical models for direct estimation of design flow. While Webster assumed binomial distribution, Wistort suggested normal approximation to the binomial distribution to estimate the peak flow for sizing pipes in BWSS. Wistort’s model can be directly used to obtain 99th percentile design flow for pipe sizing in buildings by avoiding the use of Fixture Units. Omaghomi & Buchberger (2014) found that Wistort’s method produces erroneous values for cases with np < 5 and n(1-p) < 5. Hobbs et al. (2019) argued that the accuracy of Wistort’s method is highly dependent on ‘p’ values. Modifications of Wistort’s method given by Omaghomi (2019), viz. ZTPBD and NAPBD, are used in WDC. These modifications consider the probability of stagnation in plumbing systems while calculating the peak flow. The modified Wistort’s method is suitable and the easiest method to be directly used for estimating design flow for buildings with n > 30 (Hobbs et al. 2019). In spite of this modification, Wistort’s method still uses fixture-use probability p, which is complex in nature.

As water use habits keep changing with the time, the models for demand estimation need regular updating when used for BWSS design. The difference between the actual and theoretical values is always found. Implementation of Bayes’ theorem may be useful for this purpose. Bayes’ theorem has been applied in many research areas such as the thermal comfort of buildings (Wong et al. 2014). It uses the values of an unknown parameter determined using an available mathematical model and those obtained from actual observations to estimate improved posterior values of the unknown. The application of Bayes’ theorem for updating water demand model is illustrated by Mui et al. (2008) and Wong & Mui (2018).

As design of components of any WSS is based on water demand as an inevitably important input, its accurate estimation may supposedly lead to efficient design of the system. But, the variations in instantaneous water demand are unavoidable in any circumstances. Consequently, the endeavour to estimate accurate instantaneous water demand is most likely to result in a complex analytical model. Any changes in water use occurring over a period of time due to several climatic, technological, behavioural and socio-economic factors may not be accommodated in such a model. Also, it is highly difficult to consider all the factors affecting water demand simultaneously in an analytical or mathematical model. The fact to be highlighted here is that water demand can never be predicted accurately but can be estimated with certain probability (Hunter 1940).

As most of the hydraulic systems and models are nonlinear (Tabesh & Dini 2009), a grey-box approach or soft computing tools may be effective in water demand modelling. Noting the fact that the user is the most important factor in water demand modelling, its subjective behaviour and water use habits can be used to model the residential water demand. Ultimately, fuzzy modelling and neural network techniques can comprehend such subjective behaviour of users, incorporating the uncertainty of water use.

**HYDRAULIC RELIABILITY OF BWSS**

The reliability of a system lies in its smooth functioning under varying operating conditions. For WDS and BWSS, water demand is an input that has an inherent characteristic
of uncertainty and shows variation with numerous known and unknown factors. Thus, it becomes important to know if the system can accommodate these variations in water demand and serve its purpose of supplying water to users with required flow and specified head. This tolerance in demand variation can be quantified by estimation of HR.

Tanyimboh (2003) presented three major scenarios while defining failure of WDS as its inability to perform satisfactorily (Table 1). Scenario 3 was found to be relevant in defining the HR, and accordingly Tanyimboh (2003) defined it as the ratio of mean value of flow delivered to the flow required at nodes.

In the case of BWSS, the availability of required flow at fixtures with sufficient head is a major concern while designing the system, because there is a difference in static head at a source and the fixtures. Exceedance of design capacity is less likely to occur because of the fixed number of users in a building (Scenario 1). Failure of mechanical components can be addressed by estimating the mechanical reliability of BWSS (Scenario 2).

For evaluating the reliability of a system, causes of failure to serve its intended purpose need to be identified. Gheisi et al. (2016) presented a well-organized categorization of different reliability measurement aspects for WDS (Figure 2). The various approaches to estimate reliability of WSS were also discussed. In the case of BWSS, such detailed discussion and classification of different failure scenarios is unavailable. All causes of failure in WDS might not be observed in BWSS or may be observed with different intensity than that of WDS; for example, the growth of biofilm in BWSS pipes may be less frequent than pipes in WDS, or BWSS might be less susceptible to contaminant intrusion than that of WDS. These differences in causes of failure can be accounted to the topography, surrounding elements and flow characteristics in BWSS and WDS.

### Estimation of hydraulic reliability

The estimation of HR can be approached in two ways. First, using stochastic reliability measures to evaluate reliability in terms of probability using variance, expected value or their combination. Second, with the help of indirect or surrogate reliability measures referred to as heuristic approaches. Surrogate reliability measures are computationally efficient as compared to direct measures. But the correlation between surrogate reliability measures and reliability has to be evaluated (Paez 2019). Gheisi et al. (2016) discussed the above two approaches along with the systemic-holistic approach, which uses simulation of the system as a whole to estimate the reliability of WSS.

A countable number of research studies can be found on HR of BWSS. Gad & Abd-Elaal (2015) presented the hydraulic reliability-based design of BWSS with direct supply system using HDA. The indices used to evaluate reliability were the Resilience Index, Minimum Surplus Head and Failure Index. Extending their study on reliable design of BWSS, Abd-Elaal & Gad (2018) compared reliability of a looped networks with a branched network for BWSS. A typical BWSS network of a three-storey building was used. The looped water supply network was found to have higher overall HR than the branched

---

**Table 1** | Scenarios for abnormal operating condition in water distribution system (Tanyimboh 2003)

| Scenario no. | Characterization | Reason |
|--------------|------------------|--------|
| 1            | Design capacity exceeded | Increased demands with time |
| 2            | Subnormal system performance | Failure of mechanical components |
| 3            | Reduction in capacity of water distribution system | Aging, increased pipe roughness, tuberculation etc. |
network for a building. Often, BWSSs have dead-end or tree system of pipe network with less reliability as compared to looped network system.

Reliability of a WDS is a widely researched area. Various approaches and indices are available to define the reliability of WSS. Tanyimboh & Templeman (2000) estimated HR of looped WDN considering constant demand values and expressed it as

\[
R = \frac{1}{T} \left[ p(0)T(0) + \sum_{m=1}^{M} p(m)T(m) + \sum_{m=1}^{M-1} p(m, n)T(m, n) \right] + \frac{1}{2} \left[ 1 - p(0) - \sum_{m=1}^{M} p(m) - \sum_{m=1}^{M-1} \sum_{n=m+1}^{M} p(m, n) - \ldots \right] \tag{1}
\]

where, \( R \) – Reliability;
- \( M \) – Number of pipes;
- \( p(0) \) – Probability of no pipe being out of service;
- \( p(m) \) – Probability of pipe \( m \) out of service;
- \( p(m, n) \) – Probability of pipes \( m \) and \( n \) out of service;
- \( T(0) \) – Total flow with no pipe out of service; and
- \( T \) – The sum of the nodal demands.

The modification of Equation (1) can be used for estimating HR of BWSS with a looped pipe network considering different base demand values of each fixture. In a branched pipe layout, which is commonly observed in BWSS, the case of a pipe being out of service will be more significant as it can affect the water supply of few or more users simultaneously. A significance factor has to be associated with the type of pipe while calculating the reliability of BWSS using Equation (1); for example, a fixture supply pipe will have a lesser significance factor than a branch pipe or service pipe.

Awumah et al. (1990) proposed the use of entropy as a reliability indicator for WDS using Shannon’s (1948) entropy function. A well-defined entropy function to estimate reliability of WDS was given by Tanyimboh (1993). Entropy quantifies an uncertainty in the probabilistic events. The uncertainty in water demands and probability of mechanical or hydraulic failure can be modelled using entropy. More entropy signifies scattered flow distribution in the network and hence more reliability. Calculation of entropy for nodes (Equation (2)) only requires values of nodal demands, supplied flow, layout of a network and feasible set of flow directions (Tanyimboh & Sheahan 2002).

\[
S = - \sum_{j \in IN} \frac{Q_j}{T} \ln \left( \frac{Q_j}{T} \right) - \frac{1}{T} \sum_{j=1}^{N} T_j \left[ \ln \left( \frac{Q_j}{T_j} \right) + \sum_{i \in N_j} \frac{q_{ij}}{T_j} \ln \left( \frac{q_{ij}}{T_j} \right) \right] \tag{2}
\]

where, \( S \) – Entropy of WDN;
- \( IN \) – set of source and demand nodes;
- \( T \) – Total supply;
- \( T_j \) – Total flow reaching node \( j \);
- \( q_{ij} \) – Flow rate in pipe \( ij \);
- \( Q_j \) – Nodal demand;
- \( N_j \) – Number of adjacent nodes connected to node \( j \).

Nodal entropy is important for BWSS as an end node in BWSS represents a fixture where a water-use event occurs. Equation (2) considers demand satisfaction irrespective of the head at a fixture. As the problems of insufficient head at fixtures are quite common in BWSS, especially in multi-storey buildings, HDA is carried out for BWSS design and analysis. Thus, head at a fixture is a critical factor for estimating reliability of BWSS.

The layout of BWSS is more volatile compared to WDS. The arrangement of flats/apartments in a building, location of water supply fixtures, tanks and space availability govern the plumbing layout within the buildings. Each building might create a unique BWSS network layout. Entropy function can be useful for selecting the optimal pipe layout from given possible layouts of the pipe network in BWSS.

To estimate the HR of BWSS, energy-based surrogate reliability measures would be more relevant and suitable as they consider the heads at source and nodes. The Resilience Index (RI) given by Todini (2000) indirectly measures the energy at nodes in terms of surplus head (beyond minimum specified head), which can be utilized during critical operating conditions (Equation (3)).

\[
RI = \frac{\sum_{i=1}^{N_n} q_i (h_i - h_{\text{min}})}{\sum_{k=1}^{N_k} Q_k H_k - \sum_{i=1}^{N_n} q_i h_{\text{min}}} \tag{3}
\]
where, \( q_i, h_i \) – Actual supplied flow and actual head at node \( i \)
- \( h_{\text{min}} \) – Minimum required head at node \( i \)
- \( Q_k, H_k \) – Flow entering network and head at the reservoir respectively
- \( N_n \) and \( N_r \) – Number of nodes and number of reservoirs respectively.

The modifications of RI, such as Modified Resilience Index (MRI), and network resilience (NR) (Prasad et al. 2003; Prasad & Park 2004; Jayaram & Srinivasan 2008) consider factors such as uniformity of pipes at a node and multiple sources of supply. In BWSS, pipe diameters go on reducing from service main to fixture supply pipe and telescopic design is adopted for the riser. Thus, pipe uniformity and its significance in HR of BWSS will have to studied to check its effect on reliability calculations.

Complexity in design and analysis of BWSS is primarily posed by higher demand uncertainty in BWSS. Thus, pipe sizing of BWSS itself is based on the probability of demand. A hydraulically reliable design of BWSS may be able to accommodate inevitable demand variations. Moreover, consideration to hydraulic reliability during the design of BWSS may permit an approximate estimation of water demands in BWSS. The reason lies in the concept of hydraulic reliability, which quantifies the capacity of WSS to absorb demand variations. This can aid the fact that use of soft computing techniques like fuzzy logic for the estimation of residential water demand may yield sufficiently acceptable results for the pipe sizing in BWSS when supported with estimation of hydraulic reliability.

**CONCLUSION**

A relevant literature on residential water demand modelling and hydraulic reliability is reviewed with the aim of exploring into efficient design of BWSS. Use of water is a subjective and user-dependent event affected by several factors and user characteristics. The common basic parameter, fixture-use probability (\( p \)) used in many models for instantaneous residential water demand estimation, including the Fixture Unit approach, is a very difficult variable to determine and requires a large amount of high-resolution field data. Most of the stochastic water demand estimation models use such fine-scaled data collected from a large number of households for quite a long period of time (around 1–15 years), which may not be available for a region under consideration. Thus, an alternative approach is required to model residential water demand to circumvent the need for high-resolution field data. The location-specific studies for characterizing water-use behaviour of users might be tedious, but can prove to be a more rational way to estimate water demand for the efficient design of BWSS in the respective locality. The size of an area or region under consideration for characterizing user-behaviour remains an aspect open for investigation.

Soft computing techniques like fuzzy logic and ANN can simplify the modelling of uncertainties and irregularities in residential water demand more compared to other mathematical modelling approaches. The subjective information on use of different fixtures can be obtained from users and used for developing an interaction between the user and plumbing fixtures using fuzzy logic. The water demand model based on such a data will require no costly field measurements, as its parameters such as instance, duration and frequency can be retrieved from approximate information given by users. The feasibility of such an end-use water demand model in BWSS design may be strengthened by giving due consideration to estimation of its hydraulic reliability during design. Moreover, estimation of hydraulic reliability of BWSS is essential as there are significantly higher demand variations in BWSS than those of WDS. The amalgamation of these two aspects, viz. modelling of water demand using soft-computing techniques and consideration to estimation of hydraulic reliability in the design of BWSS, can prove to be very useful to overcome problems of selecting appropriate method of pipe sizing in BWSS and efficient design of BWSS. Nonetheless, applicability and consequent use of available reliability indices, viz. entropy, RI, MRI, NR, etc. for estimating the hydraulic reliability of BWSS needs to be studied in detail.

**DATA AVAILABILITY STATEMENT**

All relevant data are included in the paper or its Supplementary Information.
REFERENCES

Abd-Elaal, A. & Gad, A. 2018 Improvement of plumbing systems performance using looped water pipe networks within buildings. Journal of Water Supply Research and Technology 67 (7), 626–633. doi:10.2166/AWUA.2018.027.

Alcocer-Yamanaka, V., Tzatchkov, V. & Arreguin-Cortes, F. 2012 Modeling of drinking water distribution networks using stochastic demand. Water Resources Management 26, 1779–1792. https://doi.org/10.1007/s11269-012-9979-2.

Altunkaynak, A. & Nigussie, T. 2017 Monthly water consumption prediction using season algorithm and wavelet transform–based models. Journal of Water Resources Planning and Management 143 (6), 04017013. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000761.

Alvisi, S., Franchini, M. & Marinelli, A. 2003 A stochastic model for representing drinking water demand at residential level. Water Resources Management 17, 197–222. https://doi.org/10.1023/A:1024100518186.

American Water Works Association (AWWA) 2004 Sizing Water Service Lines and Meters: Manual of Water Supply Practices (M22). Denver, Colorado, USA.

Awumah, K., Goulter, I. & Bhatt, S. 1990 Assessment of reliability in water distribution networks using entropy-based measures. Stochastic Hydrology and Hydraulics 4 (4), 309–320. https://doi.org/10.1007/BF01544084.

Bao, Y. & Mays, L. 1990 Model for water distribution system reliability. Journal of Hydraulic Engineering 116 (9), 1119–1137. doi:10.1061/(ASCE)0733-9429(1990)116:9(1119).

Beal, C. & Stewart, R. 2014 Identifying residential water end uses underpinning peak day and peak hour demand. Journal of Water Resources Planning and Management 140 (7), 04014008. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000357.

Bennett, C., Stewart, R. & Beal, C. 2013 ANN-based residential water end-use demand forecasting model. Expert Systems with Application 40, 1014–1023. https://doi.org/10.1016/j.eswa.2012.08.012.

Bhave, P. & Gupta, R. 2004 Optimal design of water distribution networks for fuzzy demands. Civil Engineering and Environmental Systems 21 (4), 229–245. https://doi.org/10.1080/1028660412331314564.

Blokker, E., Vlieberg, J. & van Dijk, J. 2010 Simulating residential water demand with stochastic end-use model. Journal of Water Resources Planning and Management 136 (1), 19–26. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000002.

Breese, J. 2001 Solving the mixed system problem. Plumbing Engineer. 29 (3), 39–48.

Buchberger, S. & Li, Z. 2007 PRPsym: A Modeling System for Simulation of Stochastic Water Demands. In World Environmental and Water Resources Congress: Restoring Our Natural Habitat, May 15–19, 2007, Tampa, FL, USA. https://doi.org/10.1061/40927(243)511.

Buchberger, S. & Wu, L. 1995 Model for instantaneous residential water demands. Journal of Hydraulic Engineering 121 (3), 232–246. https://doi.org/10.1061/(ASCE)0733-9429(1995)121:3(232).

Cole, D. 2011 Determining fixture units for high-efficiency plumbing fixtures. Plumbing Systems and Design July–August, 13–19.

Creaco, E., Blokker, E. & Buchberger, S. 2017 Models for generating household water demand pulses: literature review and comparison. Journal of Water Resources Planning and Management 143 (6), 04017013. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000765.

Di Palma, F., Marinis, G., Gargano, R., Granata, F., Greco, R. & Tricarico, C. 2014 The overall pulse model to predict the end use water demand. Procedia Engineering 89, 942–949. doi:10.1016/j.proeng.2014.11.528.

Di Palma, F., Gargano, R., Granata, F. & Greco, R. 2017 The Overall Pulse model for water demand of aggregated residential users. Procedia Engineering 186, 485–490. doi:10.1016/j.proeng.2017.03.260.

Ferreira, T. & Goncalves, O. 2019 Stochastic simulation model of water demand in residential buildings. Building Services Engineering Research and Technology 41 (5), 1–17. https://doi.org/10.1177/014362441986248.

Fujiwara, O. & De Silva, A. 1990 Algorithm for reliability-based optimal design of water networks. Journal of Environmental Engineering 116 (3), 575–587. doi:10.1061/(ASCE)0733-9372(1990)116:3(575).

Gad, A. & Abd-Elaal, A. 2003 Practical guidelines for reliability based design of building water supply systems. Urban Water Journal 13 (2), 94–107. https://doi.org/10.1080/1573062X.2014.993995.

Gato, S. 2006 Forecasting Urban Residential Water Demand. PhD thesis, RMIT University, Melbourne, Australia.

Gheisi, A., Forsyth, M. & Naser, G. 2016 Water distribution systems reliability: a review of research literature. Journal of Water Resources Planning and Management 04016047, 1–13. doi:10.1061/(ASCE)WR.1943-5452.0000690.

Hobbs, I., Anda, M. & Bahri, P. 2019 Estimating peak water demand: literature review of current standing and research challenges. Results in Engineering 4, 100055. https://doi.org/10.1016/j.rineng.2019.100055.

Howick, H. 1964 The pipe sizing of hot and cold-water installations, Plumbing Trade Journal, September.

Hunter, R. 1940 Methods of Estimating Loads in Plumbing Systems. Building Materials and Structures, National Bureau of Standards, Washington, DC.

Ingle, S., King, D. & Southerton, R. 2014 Design and sizing of water supply systems using loading units – time for a change? In Proceedings of the 40th CIBW062 International Symposium of Water Supply and Drainage for Buildings, 8–10 September 2014, Sao Paulo, Brazil.

International Plumbing Code. 2018 International Code Council, USA.

Jayaram, N. & Srinivasan, K. 2008 Performance-based optimal design and rehabilitation of water distribution networks using life cycle costing. Water Resource Research 44, W01417. https://doi.org/10.1029/2006WR005516.

Konen, T. & Goncalves, O. 1993 Summary of mathematical models for the design of water distribution systems with
buildings. In *Proceedings of the 20th CIBW062 International Symposium of Water Supply and Drainage Systems for Buildings*, 20–23 September 1993, Porto, Portugal.

Mazumdar, A., Jamun, H. & Das, S. 2014 *Modification of Hunter’s curve in the perspective of water conservation*. *Journal of Pipeline Systems Engineering and Practice* 5, 04013007. https://doi.org/10.1061/(ASCE)PS.1949-1209.0000150.

Mui, K., Wong, L. & Yeung, M. 2008 *Epistemic demand analysis for fresh water supply of Chinese restaurants*. *Building Services Engineering Research and Technology* 29 (2), 183–189. https://doi.org/10.1177/0143624408090205.

Murakawa, S. 1985 *Study on the method for calculating water consumption and water uses in multi-story flats*. In: *Proceedings of the 13th CIBW062 International Symposium of Water Supply and Drainage Systems for Buildings*, 9–10 April 1985, Tokyo, Japan.

National Standard Plumbing code. 2009 *Plumbing Heating Cooling Contractors National Association, USA.*

Oliveira, L., Cheng, L., Gonçalves, O. & Massolino, P. 2013 *Modeling of water demand in building supply systems using Fuzzy logic*. *Building Services Engineering Research and Technology* 34 (2), 145–163. https://doi.org/10.1177/0143624411429381.

Omaghomi, T. 2009 *Estimating Peak Water Demand in Buildings with Efficient Fixtures: Methods, Merits, and Implications*. PhD thesis, University of Cincinnati, Cincinnati, OH, USA.

Omaghomi, T. & Buchberger, S. 2014 *Estimating water demands in buildings*. *Procedia Engineering* 89, 1013–1022. https://doi.org/10.1016/j.proeng.2014.11.219.

Omaghomi, T. & Buchberger, S. 2015 *Variation in peak water demand with Building Size: Parameters and Methods*. In *1st International WDSA/ CCWI 2018 Joint Conference*, 23–25 July 2018, Ontario, Canada.

Paez, D. 2009 *Developing A Framework for the Reliability Analysis of Water Distribution Systems*. PhD thesis, Queen’s University Kingston, Ontario, Canada.

Prasad, T. & Park, N. 2004 *Multiobjective genetic algorithms for design of water distribution networks*. *Journal of Water Resources Planning and Management* 130 (1), 73–82. https://doi.org/10.1061/(ASCE)0733-9496(2004)130:1(73).

Prasad, T., Sung-Hoon, H. & Namsik, P. 2003 *Reliability based design of water distribution networks using multiobjective genetic algorithms*. *KSCE J Civil Engineering* 7 (3), 351–361. https://doi.org/10.1007/BF02831784.

Rathnayaka, K., Malanoa, H., Arora, M., George, A., Maheepala, S. & Nawarathna, B. 2017 *Prediction of urban residential end-use water demands by integrating known and unknown water demand drivers at multiple scales I: model development*. *Resources Conservation and Recycling* 117, 85–92. https://dx.doi.org/10.1016/j.resconrec.2016.11.014.

Shannon, C. 1948 *A mathematical theory of communication*. *The Bell System Technical Journal* 27, 379–423. 625–656. https://doi.org/10.1002/j.1538-7305.1948.tb00917.x.

Suh, D. & Ham, S. 2016 *A water demand forecasting model using BPNN for residential building*. *Contemporary Engineering Sciences* 9 (1), 110. http://dx.doi.org/10.12988/ces.2016.512314.

Tabesh, M. & Dini, M. 2009 *Fuzzy and neuro-fuzzy models for short-term water demand forecasting In Tehran*. *Iranian Journal of Science & Technology, Transaction B, Engineering* 33, 61–77.

Tanyimboh, T. 1993 *An Entropy-Based Approach to the Optimum Design of Reliable Water Distribution Networks*. PhD thesis, University of Liverpool, Liverpool, UK.

Tanyimboh, T. 2003 *Reliability Analysis of Water Distribution Systems*. In *Urban and Rural Water Systems for Sustainable Development: Proceedings of the 50th IAHR Congress*, 24–29 August 2003, Thessaloniki, Greece, pp. 321–328.

Tanyimboh, T. & Sheahan, C. 2002 *A maximum entropy based approach to the layout optimization of water distribution systems*. *Civil Engineering and Environmental Systems* 19 (3), 223–253. doi:10.1080/10286602121433504135.

Tanyimboh, T. & Templeman, A. 2000 *A quantified assessment of the relationship between the reliability and entropy of water distribution systems*. *Engineering Optimization* 33 (2), 179–199. https://doi.org/10.1080/030521500894092.

Todini, E. 2000 *Looped water distribution networks design using a resilience index based heuristic approach*. *Urban Water Journal* 2, 115–122. doi:10.1016/S1462-0758(00)00049-2.

Uniform Illustrated Plumbing Code-India. 2018 *International Association of Plumbing and Mechanical Officials India.*

Vijayalaksmi, D. & Babu, K. 2015 *Water supply system demand forecasting using adaptive neuro-fuzzy inference system*. *Aquatic Procedia* 4, 950–956. doi:10.1016/j.aqpro.2015.02.119.

Webster, C. J. D. 1972 *An investigation of the use of water outlets in multi-storey flats*. In *Proceedings of the 1st CIBW062 International Symposium of Water Supply and Drainage Systems for Buildings*, 14–26 September 1972, Herts, UK, pp. 23–42.

Willis, R., Stewart, R., Giurco, D., Talebpour, M. & Moussavnejad, A. 2013 *End use water consumption in households: impact of socio-demographic factors and efficient devices*. *Journal of Cleaner Production* 60, 107–115. https://doi.org/10.1016/j.jclepro.2011.08.006.

Wistort, R. 1994 *A new look at determining water demand in buildings: ASPE direct analytical method*. In *Technical Proceeding of American Society of Plumbing Engineers Convention*, 23–26 October 1994, Kansas City, MO, USA, pp. 17–34.

Wong, L. & Mui, K. 2018 *A review of demand models for water systems in buildings including a Bayesian approach*. *Water* 10 (1078), 1–25. https://doi.org/10.3390/w10081078.

Wong, L., Mui, K. & Cheung, C. 2014 *Bayesian thermal comfort model*. *Building and Environment* 82, 171–179. doi:10.1016/j.buildenv.2014.08.018.

First received 16 September 2020; accepted in revised form 10 January 2021. Available online 21 January 2021.