Developing a new design approach to estimate design flow rate in non-residential buildings

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Abstract

Making an accurate estimation of peak water demand in buildings is essential for engineers and designers in order to ensure proper sizing of water supply systems, storage tanks, boilers, and booster pumps. Over recent years, the amount of potable water used in buildings has reduced considerably as a result of the prevalence of water-efficient appliances and a heightened awareness of the need to conserve water. This has, in part, led to oversizing of water supply networks; a phenomenon that has given cause for concern to those responsible for the design of building plumbing systems. This oversizing problem does not only result in a material and financial cost, it also has negative health consequences.

In the UK, despite a clear reduction in consumption at end-use points, traditional design approaches are still used for determining design flow rate. Although different design methods have been presented in various British standards and guidance documents, all use the Loading Unit (LU) approach, which is based on the application of probabilistic techniques, to estimate the design flow for both residential and non-residential buildings. In recent studies, the focus has generally been on residential buildings and there has been little, if any, research to assess the validity of current design methods for non-residential buildings. This study, therefore, focuses on developing a new design approach to estimate demand flow in non-residential buildings.

This research starts by providing background information on the water situation in the UK and discusses the reasons for oversizing and its consequences. Water demand is also discussed, as is water conservation, per capita water consumption and the demand from micro-components. In addition, the history of system design and the most commonly used UK design approaches are discussed. After undertaking a critical review and comprehensive investigation of statistical methods and recent studies used to estimate demand flow, a new design methodology for estimating water demand, specifically for non-residential buildings, is introduced. This has also allowed for the presentation of a new stochastic model, namely the Water Demand Estimation Model (WDEM).

The model is underpinned by the interaction between users and the provision of sanitary appliances in conjunction with the generation of a comprehensive range of probabilities to capture all possible simultaneous uses of appliances. The Monte Carlo technique has been applied to calculate flow rate values based on a given number of users. A specific type of non-residential building i.e. the ‘workplace’ has been selected for application of the model and for which new design equations have been derived. Taking into account the water saving appliances used in modern plumbing systems, five design equations have been derived based on efficiency levels of corresponding appliances. In order to validate the model and to assess its accuracy, high quality flow rate data was gathered from three case study buildings. The effectiveness of the WDEM and its impact on the oversizing of water systems has been confirmed by comparing simulated, measured and design flow rates. The results show that the simulated demand is very close to the measured flow rate, and that its use results in a significant reduction of design flow rate compared to those determined by using current design codes.

The main outcome of this study is hence a novel approach for the estimation of demand flow for non-residential buildings and a set of design equations to estimate the simultaneous demand flow rate for workplaces. This new approach will be of value to all engineers and designers who seek to establish a more accurate estimation of water demand in buildings.

Acknowledgements

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Declaration Statement

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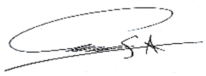
Signature: 		Date:	14/07/2022

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Q''	Design flow rate based on available design codes and guides
n	Number of sanitary appliances of the same type
N	Total number of mixed appliances
q	Flow rate of individual appliances
q_a	Total flow rate of appliances of the same type
q_t	Total flow rate of mixed type appliances
g	Number of group (type) of appliances
p	Probability that an appliance is in use (*p*-value)
p'	Average probability (*p*-value) for a group of appliances
f	Probability that an appliance is not in use
T	Average time between successive using of an appliance
t	Average duration of time that an appliance is in use
x	Number of males or females
X	Total number of users (male and female)
P	Probability of using appliances in a water use event
k	Number of appliances in use out on *n* number of the same type
$P(k)$	Probability of *k* number of appliances being in use out of *n* number
K	Number of mixed appliances in use out of *N* number
$P'(K)$	Approximate probability of *K* number of mixed appliances being in use out of *N* number
P_r	Probability of occurring a value of flow rat q_t in the simulation
T_r	Number of simulation trials in WDEM
Q	Simulated flow rate obtained from WDEM
Q_{max}	Maximum simulated water demand
$Q_{0.99}$	99^{th} percentile of simulated water demand
Q_d	Design flow rate
Q'	Measured/observed flow rate
Q'_{max}	Maximum observed water demand
$Q'_{0.99}$	99^{th} percentile of observed water demand

List of Publications

Mohammed, S., Jack, L. B., Patidar, S. and Kelly, D. A. (2018) '*Assessing overestimation of water demand in different types of non-residential buildings in the UK*', in CIB W062 45th International Symposium August 8th -10th 2019. Melbourne- Australia.

Mohammed, S., Jack, L. B., Patidar, S. and Kelly, D. A. (2018) '*Defining the oversizing problem and finding an optimal design approach for water supply systems for non- residential buildings in the UK*', in CIB W062 44th International Symposium August 28th -30th 2018. Azores- Portugal, pp. 1–16.

Adeloye, A. J., Soundharajan, B. S. and Mohammed, S. (2016) '*Harmonisation of Reliability Performance Indices for Planning and Operational Evaluation of Water Supply Reservoirs*', Water Resources Management, 31(3), pp. 1013–1029.

Chapter 1- Introduction

1.1 Introduction

Water can be defined as an essential resource for life and one that heavily influences living standards and public health. One of the major environmental problems that faces many countries in the world is water scarcity, in particular in those regions with low water availability. Global warming makes the problem of water availability even more serious when the amount of surface water is affected by a reduction in rainfall, especially in drought seasons, and some ground water reservoirs may be contaminated with salt as a result of rising sea level. In addition, insufficient demand management and inefficient water use can make the problem worse and more complex (Butler and Memon, 2006; Proença and Ghisi, 2010).

At the property scale, different methods have been practised to encourage more sustainable and efficient use of this essential resource, such as using water efficient appliances, rainwater harvesting and water reuse systems. Many studies have been carried out internationally targeting improved efficiency in water use, and the results confirm that increasing the efficiency of sanitary appliances leads to considerable reductions in water demand and also translates into significant cost savings (Butler and Memon, 2006; Proença and Ghisi, 2010). Most appliance manufacturing companies produce low water use fittings and they label their products to show the water consumption in order to encourage people to choose efficient models. In addition, people's behaviour has changed as a result of interpretive and educational campaigns to raise awareness of the importance of water and avoiding wastage. Furthermore, working habits have become more flexible and the changing ratio of men to women has caused a change of behaviour among water users (Tindall and Pendle, 2017).

Despite the obvious changes in sanitary appliances and users' behaviour, traditional design approaches are still used for determining design flow rate, which results in an overestimation of water demand. In order to provide a better estimation of demand flow in buildings, many studies have been undertaken globally. In most of these studies, the focus has been on residential buildings and there has been little research to assess the validity of current design methods or to develop new methods for non-residential buildings. This study, therefore, addresses the oversizing problem and defines a new design methodology for estimating water demand, specifically for non-residential buildings.

1.2 Statement of the problem

Predicting water demand in buildings is not straightforward as it requires information about complex factors such as the intensity and frequency of use. This issue was first investigated by Dr Roy B. Hunter in the 1940s who used principles of probability to estimate design load. Hunter's Curve was produced by using a "fixture unit" to predict design flow rate in buildings. Hunter's approach, which will be discussed in more detail in Chapter 2, was widely accepted and used as a design method in most plumbing codes worldwide. However, there has been growing agreement among designers that the application of Hunter's method now results in overdesign of the water supply system. This is because of two main reasons: firstly, the design method. Since most design methods use the "fixture unit" derived from a probabilistic model to estimate water demand with an underpinning assumption of appliances being used simultaneously in congested services in which there is a queue of users waiting to use each appliance; an aspect of the deign approach which often does not hold. In addition, the probabilistic approach uses mathematical parameters to describe the duration of the flow, the appliance flow rate and how often the appliance is in use. These parameters have changed considerably and water demand calculated for plumbing appliances from the 1940s is not applicable to the new types of water conserving appliances now used in modern plumbing systems. Secondly, there have been many changes in people's behaviour over the last few decades, including growing environmental awareness and a willingness to engage with the environmental agenda (The Institute of Plumbing, 2002; Wong and Mui, 2008; Buchberger, Omaghomi, Wolfe, Hewitt and Cole, 2015a).

In the past few years, different studies have discussed the reasons and scale of overestimation in water demand. For instance, Chanan, White, Howe and Jha (2003) showed that in non-residential buildings of typical size and configuration, a reduction of up to 80% in water demand can be achieved through the integration of water efficiency measures and water conservation schemes. In addition, Milan (2006) discussed that use of one water saving toilet by the householder leads to a reduction in water demand of 10-11%. Furthermore, Fan *et al.* (2014) also discussed how water consumption has reduced as a result of changing people's behaviour. They showed how water consumption decreased by 57% in Melbourne, Australia as a result of education and public awareness campaigns, and how water consumption has been reduced by 18% and 20% in Spain and California, respectively, because of improved water conservation awareness. More importantly, the use of water-efficient appliances is also effective in non-residential buildings where double and low flush WCs, sensor flow or self-closing taps, and sensor/waterless urinals can be used instead of traditional models. For example, Waggett and Arotsky (2006) stated that the night-time use of water was reduced from 300 *l/hr* to 10 *l/night* when urinal controls were changed in the Environment Agency offices in the North West of England, and water use was reduced by 41% after replacement of the cisterns in council offices in Kingston, London.

As a consequence, most design approaches result in oversizing of the water supply network; a phenomenon that has given cause for concern among those responsible for the design of building plumbing systems and for public health engineering communities. The traditional design methodology has not undergone a corresponding change and there has been no considerable updating of design codes (Blokker, 2010; Agudelo-vera, Pieterse-Quitijns, Scheffer and Blokker, 2013; Buchberger, Omaghomi, Wolfe, Hewit and Cole, 2017; Tindall and Pendle, 2017).

1.3 The consequences of oversizing the water system

Despite considerable efforts by water companies to provide high quality water, it is recognised that quality may deteriorate in water distribution systems. The oversizing problem has a direct effect on water quality due to the link with pipe size, for example, residual disinfection decay, contaminant propagation, biofilm formation, corrosion, disinfection by-product formation and particle accumulation and mobilisation (Blokker, 2010). Pieterse-Quirijns et al. (2013, 2014) also discussed how oversizing can lead to water quality problems such as discolouration. It may also result in stagnant water in the pipes and encourage the growth of Legionella which is acknowledged as a global problem, particularly in non-residential buildings. Oversized pipework also reduces water velocity in the system, causing the water to remain in the pipe lines longer than is ideal for hygiene and health reasons. This problem becomes more serious in tall buildings where both the domestic cold and hot water pipelines run through the same riser space, which causes undesirable heating of the cold water (Tindall and Pendle, 2017). In addition, oversized water systems are usually much less energy efficient and therefore cost more in terms of operation, in particular when oversizing of water systems not only affects the cost of pipes but also leads to oversizing of storage tanks, booster pumps, and water heating devices, wasting both money and energy (Blokker, 2010; Pieterse-Quirijns *et al.*, 2013, 2014; Omaghomi and Buchberger, 2014; Jack, 2017).

Therefore, it is important to place emphasis on improving the methodology for estimating peak demand in new buildings, especially because water conservation schemes and use of water-saving appliances have now been widely adopted by most of the plumbing codes across the world.

1.4 Water demand in non-residential buildings

Most design guides focus on determining water demand in residential buildings and there is no specific classification based on buildings' usage; this means that guides leave much to the judgement of designers, regardless of the type of building. Water demand in residential buildings has been shown to vary widely depending on a number of factors such as social patterns, income, water price, climate, and stand size. Meanwhile, in non-residential buildings, water demand is less predictable as the user plays a key role in establishing the demand pattern (Ilemobade, Van Zyl and Van Zyl, 2010). Furthermore, using water during the daytime is a specific feature that may be completely different to the pattern for residential users. Pieterse-Quirijns et al. (2013) stated that, in the Netherlands, the amount of non-residential water demand accounts for around 28% of the total water distributed. In the United States, commercial and institutional water use amount to around 17% and 15% respectively (US EPA, 2009). In the UK, non-household water use accounts for 25% and in England and Wales the figure is similar at 23% (Butler and Memon, 2006). Figure 1-1 shows a breakdown of the public water supply in the UK by volume (McDonald, Butler and Ridgewell, 2015). Non-residential buildings are made up of many systems that depend on water. With today's desire to save water and energy, water conservation has been widely applied, even if just at the appliance level, and has resulted in a clear reduction in flow rate at the end-use points.

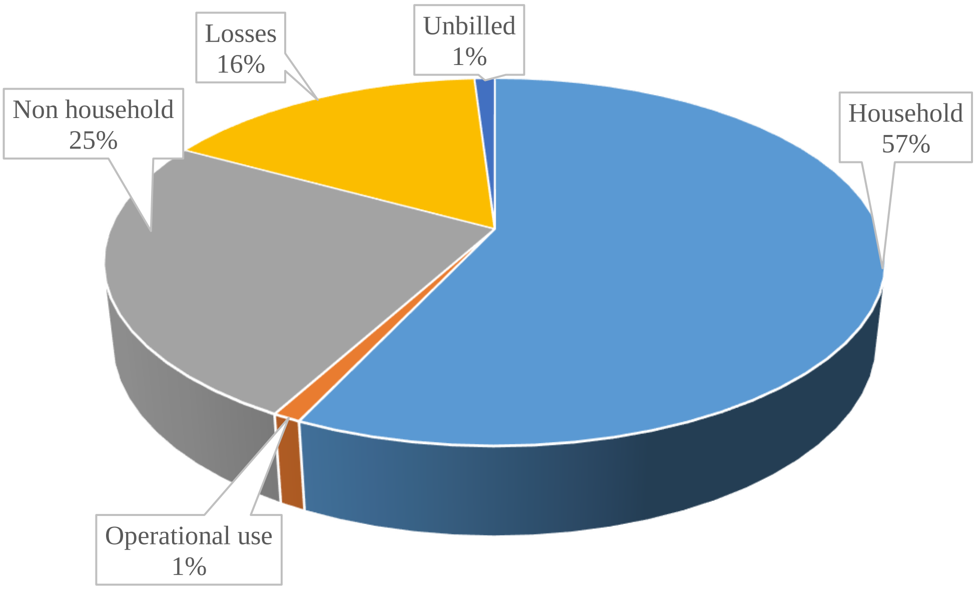


Figure 1-1 Breakdown of the public water supply (Butler and Memon, 2006, p. 288)

1.5 Aims and objectives

A number of studies have been carried out to help establish a new design approach that might work globally for better estimation of design flow rate in buildings. Most of this research has focused on residential buildings, while little has been done to address overestimation of the design flow for non-residential buildings. In the UK, a project entitled the Loading Unit Normalisation Assessment (LUNA) was launched to establish an improved model for sizing domestic hot and cold water systems in residential buildings. In parallel, the intended aim of this research is to develop a method for better estimation of water demand specifically for non-residential buildings that takes account of the considerable changes in people's behaviour and in the water consumption of sanitary appliances. To achieve this, the study focuses on the following objectives:

I. assess different types of statistical models such as probabilistic, numerical and stochastic models and select the best approach that can be used to estimate the design flow rate for non-residential buildings.

II. develop a new approach for water demand modelling in non-residential buildings and derive new design equations for a specific type of non-residential building; herein the 'workplace' building.

III. gather in-situ flow data to validate the new model and ensure that it can be used to estimate water demand with an acceptable level of accuracy.

IV. understand water usage patterns in non-residential buildings and establish the important indicators for water demand estimation, such as peak hours of usage.

1.6 Significance of the study

It is essential for all types of buildings to have a water supply system that can deliver an adequate amount of water to all draw-off points all the time. To achieve this and to provide a reliable water supply system, the maximum demand flow should be accurately determined. Previous studies have confirmed that current design guides result in overestimation of design flow rate in buildings and have also discussed the undesirable consequences of oversizing.

Developing a new design approach for better estimation of design flow rate will eliminate designers' concern with regard to oversizing. This will result in the design of more accurate and efficient water network systems, considering energy efficiency, health consequences and sustainability in buildings. This research provides a new model that can be used for calculating water demand in non-residential (workplace) buildings which will help to calculate more accurately the size of pipes, storage tanks, boilers and booster pumps, thereby saving both money and energy.

In addition, the new model will provide a differentiation in design method for calculating design flow rates for residential and non-residential buildings. Having a specific design method for non-residential buildings is essential because this type of building has a diurnal water use pattern which is totally different from that for a domestic setting. The new model can easily be extended to apply to different types of non-residential buildings given that it depends on information on sanitary appliances and users as input variables instead of flow rate data.

1.7 Thesis outline

This thesis details the research undertaken to investigate the oversizing problem and develop a stochastic model for estimating water demand in non-residential buildings.

Chapter 1 defines the research scope by explaining the essentials of the subject matter and stating the problem. The main aims and objectives of the project are also summarised.

Chapter 2 presents the research background by describing the water situation in the UK and the challenges of maintaining a balance between demand and supply under the pressures of climate change, population growth and environmental awareness. It defines some important terms related to water demand and explains how water demand has altered in response to changes in peoples' behaviour and the use of water-saving sanitary appliances. It also discusses the sizing methods used in the UK, the assumptions they make to generate LUs, and the diversity created during conversion of LUs to flow rates.

Chapter 3 describes the methodology of developing a new model and meeting the necessary requirements. It discusses different types of statistical models and approaches that can be used to estimate design flow rate in buildings. The necessary requirements to develop the model are described, including information about buildings, users, sanitary appliances and flow rate measurements.

Chapter 4 introduces a new design model, namely the Water Demand Estimation Model (WDEM), which is a stochastic model developed to estimate design flow rate in non-residential buildings. It contains the final design equations for workplace buildings that can be used to calculate design flow.

Chapter 5 presents the procedures of in-situ flow rate measurement and water usage patterns for a range of buildings from small to medium scale. Description of the case study buildings, flowmeters, installation, accuracy, technical requirements and transferring the data are explained in this chapter.

Chapter 6 focuses on validation of the model and the new design equations for the workplace. The data collected was used to validate the WDEM and to compare design and simulated flow rate with measured flow. It presents the scale of overestimation introduced by the current design methods and shows how use of the WDEM yields a significant reduction in design flow rate.

Chapter 7 sets out the conclusions of this study by summarising the development of the model and its role in reducing the oversizing problem in water supply networks. This chapter also presents a discussion on the limitations of application of this research and provides recommendations for possible further development of the work.

Chapter 2 Background study of water situation and investigating design methods

2.1 Introduction

Unlike a static resource such as land, water can be defined as a complex resource as it occurs in a very dynamic cycle that involves rain, runoff and evaporation, with huge temporal and spatial variations as well as variations in quality that govern its value to human beings and ecosystems (Rijsberman, 2006). Understanding water consumption trends is necessary to determine the availability of sufficient freshwater to meet future demand and to assess its impact on water demand. Thus, providing potable water to the customer requires the proper design, construction and operation of a complex and elaborate infrastructure capable of collecting, treating and delivering high quality drinking water to the population (Buchberger, Blokker and Cole, 2012).

One of the important strategies to meet water demand is to maintain a balance between supply and demand. Regardless of the need to provide new water sources, there is a realisation that developing new sources alone is insufficient for providing sustainable water supply systems, and demand management should focus on more efficient and sustainable approaches such as using more efficient appliances, reducing losses and waste, and water recycling. Based on these actions and considerations, the amount of water required at the end use point (sanitary appliances) has considerably changed. Thus, it has become clear that the traditional methods for the estimation of demand flow which were developed over 70 years ago (Buchberger *et al.*, 2012) should no longer be used for new plumbing systems. As a response to the changes in water use and management, the plumbing codes and guides have occasionally been updated since the first use of the LU method, aiming to improve the accuracy of design methods. In the UK, although the design guides have also been updated, no meaningful changes have been implemented within the methodology of calculating design flow rate as all are based on the LU principle originating from Hunter's method.

This chapter aims to provide a general background on the water situation and on demand flow estimation. It explains how the oversizing problem has appeared in water supply systems as a result of a change in the amount of water used and in usage patterns in buildings. The most commonly used design standards and guides in the UK are also investigated and their differences assessed in terms of their application to non-residential buildings.

2.2 Water availability and scarcity situations

Providing sufficient drinking water for populations around the world has become a big issue even in rainy countries such as Britain (Butler and Memon, 2006, p. 216), the problem being where and when the rain falls. Freshwater provision is a crucial factor in an array of global challenges ranging from health, poverty and malnutrition to sustainable natural resources management. There are many reasons why fresh water has become scarce and a more precious resource year after year, such as population growth, climate change, inefficient water use, underinvestment in infrastructure, economic and political constraints and environmental protection (Butler and Memon, 2006; DEFRA, 2014; Burns, 2016). In addition, maintaining a constant water supply may be a challenge because of situations such as increasing demand that cannot be met by the treatment plant, lack of adequate storage capacity, other communities drawing water from the same source and leakage in the pipe networks (Hickey, 2008).

Population growth, urbanisation, improved lifestyle and the impacts of climate change are all key factors that influence growing demand for water globally. For instance, it is predicted that more than a third of the population of developing countries or a quarter of the global population will face water stress by 2025 (Seckler, Barker and Amarasinghe, 1999), and more than half the global population will be living in areas experiencing water scarcity by 2050 (Rijsberman, 2006). The seriousness of this issue is highlighted by an indicator showing that half a billion of the world's population is already experiencing water scarcity (Mekonnen and Hoekstra, 2016), and 1.42 billion people currently have no access to clean water and live in areas of high water vulnerability (UNICEF, 2021), as shown in Figure 2-1. These signs provide a sufficiently strong indicator that global water demand will continue to increase, while alongside this, it is not clear how sources of water will develop to meet demand. Furthermore, water demand per capita to satisfy daily needs in coming decades will be further influenced by living standards, personal choices and different water policies.

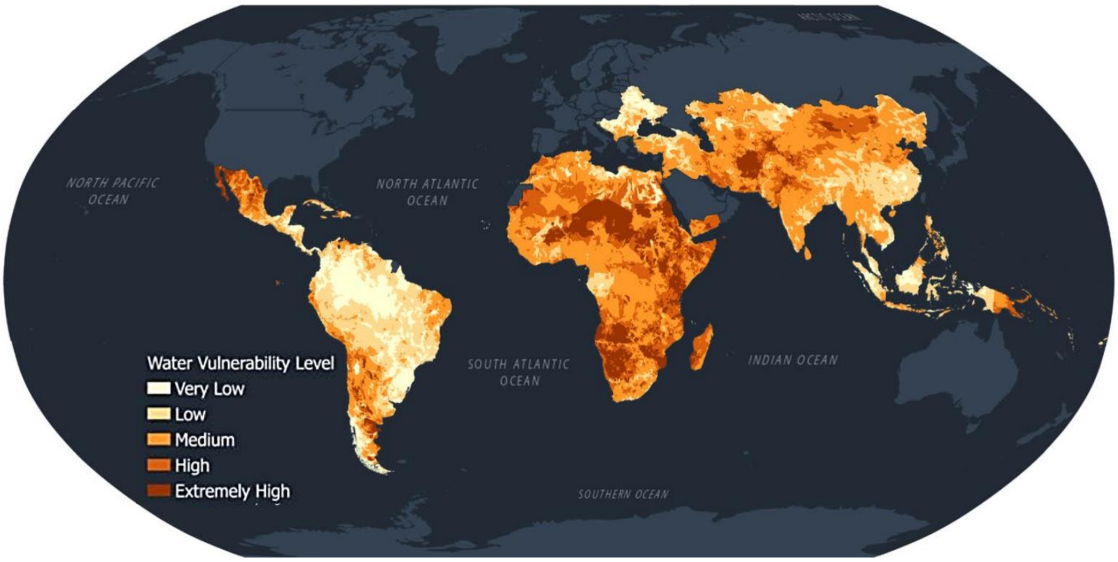


Figure 2-1 Map of water vulnerability levels in the world (UNICEF, 2021)

In the UK, the quality and quantity of all surface water and ground water are determined by the land surface which provides the catchment area. Spatial heterogeneity in topography, soils, geology and land use leads to significant local variations in water quantity and quality, while floods and droughts are results of temporal heterogeneity (Weatherhead and Howden, 2009). The vulnerability to drought hazard has reached the alert threshold of 20% according to the Water Exploitation Index which depicts water abstraction as a portion of the freshwater resource; therefore, the UK has been defined as a water-stressed region by the European Environment Agency (EEA, 2019). The water resources available for abstraction were assessed by Catchment Abstraction Management Strategies (CAMS) in order to show where water is potentially available for abstraction, how much freshwater resource is reliably available, the amount of water already licensed for abstraction and how much water the environment needs. There is significant pressure on water resources, not just in the drier South East and Eastern England but across the whole of England and Wales. The water resources availability map (Figure 2-2) shows that there are many areas where there is no water available for abstraction, and some areas are over licensed or over-abstracted and require restoration of a sustainable abstraction regime (Environment Agency, 2008). Thus, net abstractions of surface and ground water are approaching environmental limits in many UK streams and rivers, especially during summer low flow periods.

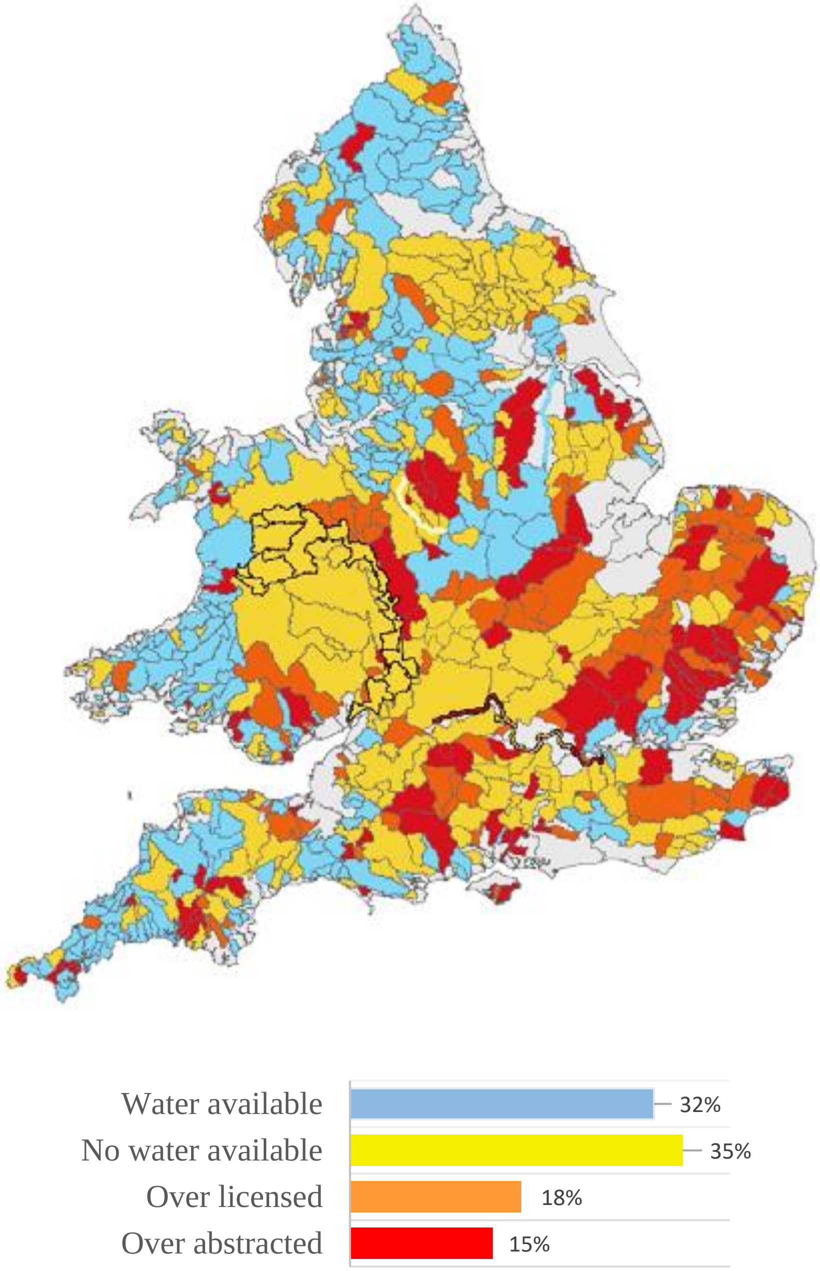


Figure 2-2 Water available for abstraction (surface water combined with groundwater)(Environment Agency, 2008)

As shown in Figure 2-2, water availability status can be classified into four groups:

- Water available (blue): water is likely to be available at all flows including low flows; restrictions may apply.

- No water available (yellow): no water is available for further licensing at low flows; water may be available at higher flows with appropriate restrictions or through licence trading.
- Over-licensed (orange): current actual abstraction is such that no water is available at low flows. If existing licences were used to their full allocation they could cause unacceptable environmental damage at low flows. Water may be available at high flows with appropriate restrictions or through licence trading.
- Over-abstracted (red): existing abstraction is causing unacceptable damage to the environment at low flows. Water may still be available at high flows with appropriate restrictions or through licence trading (Environment Agency, 2008).

In the case of Scotland, because of the predominant south-westerly winds crossing the Atlantic, it has a temperate climate that can be defined as wet and mild, with day-to-day weather being mostly changeable. In addition, climate change is likely to increase uncertainty over water availability and may cause issues in areas that have not previously experienced water scarcity (SEPA, 2019b). Scotland, therefore, is also vulnerable to periods of dry weather resulting in pressure on water users and the environment. Despite having a higher total rainfall than the rest of the country, rainfall variation follows the same trend of east-west wet-dry as the rest of the UK. Such a water situation can lead to intermittent flows which affect hydrological connectivity, water quality, biodiversity, pollution, and water supply and abstractions (Visser-Quinn, Beevers, Lau and Gosling, 2021). The latest water scarcity report by SEPA (2021) shows that there are some areas in Scotland that experience significant alert levels of water scarcity as shown in Figure 2-3.

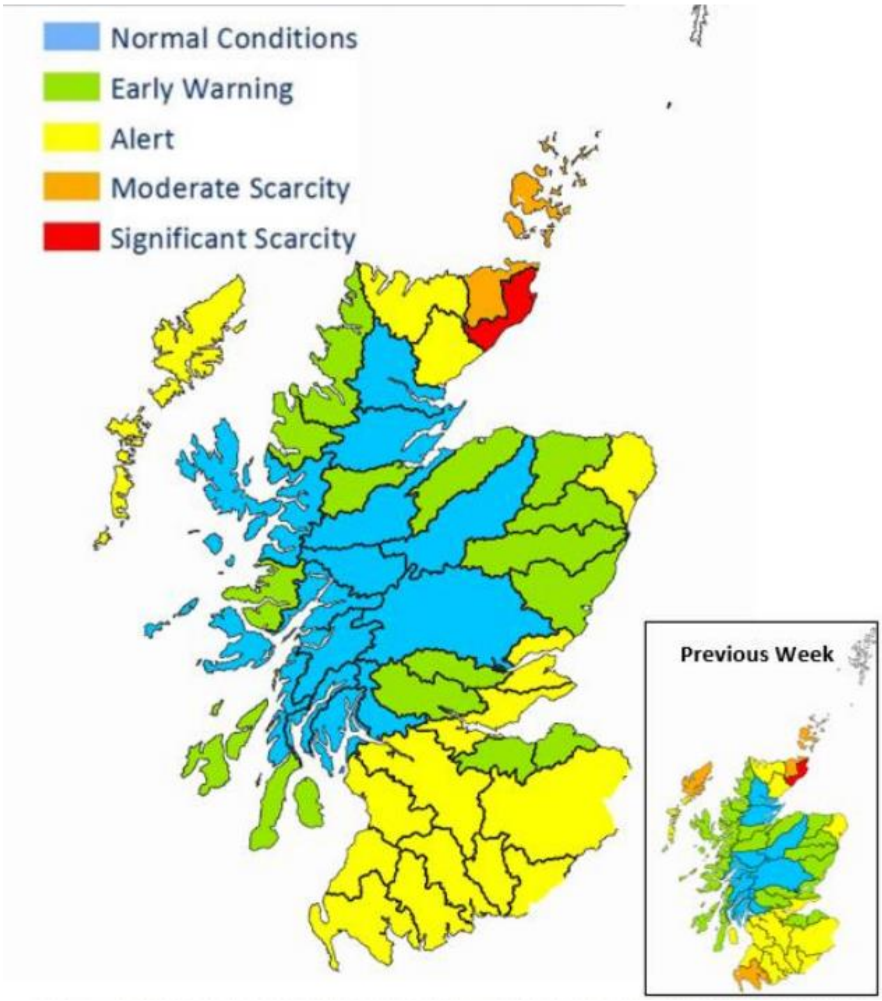


Figure 2-3 Water scarcity levels in Scotland (SEPA, 2021)

2.3 Water conservation and its effect on water demand in buildings

Effective projections of use and managing the demand for water are crucial to ensure that government, water firms, businesses and regulators can plan how to meet and manage demand in future (DEFRA, 2014). There are many challenges to maintaining the balance between water supply and demand, such as climate change, demographics, increasing rates of ground water extraction, and increased chemical and organic pollution in water resources (Butler and Memon, 2006). This means that with the significant likelihood of more severe and frequent droughts, there will be less water available in the future if necessary actions are not taken. There are two options for addressing this challenge: managing demand to avoid new supplies and/or meeting demand with new supplies (POST, 2000). The traditional engineering solution for solving supply deficits was generally to supply more: to store, abstract, treat and distribute more water to customers. This can be achieved by capturing rainfall and providing storage of water in aquifers, wells, and rivers or in dams, reservoirs and tanks. These usually need traditional engineering skills to deliver the necessary infrastructure and collect enough water to meet demand (Burns, 2016). Meanwhile, adaptation to and mitigation of climate change, competition for water resources, and preservation of ecosystems all increase pressure to find alternative or new sources.

Consequently, these traditional solutions are less acceptable nowadays and sustainable approaches are preferred. These sustainable approaches generally focus on managing demand and making water supply services more adaptable, resilient and flexible. Bailey *et al.* (2019) discussed how rising water scarcity, the need for improved water efficiency and pressure for increased sustainability will drive a reduction in water consumption. A useful structure for considering demand management is the standard 'reduce, reuse, and recycle' hierarchy as used in the management of waste, Figure 2-4.

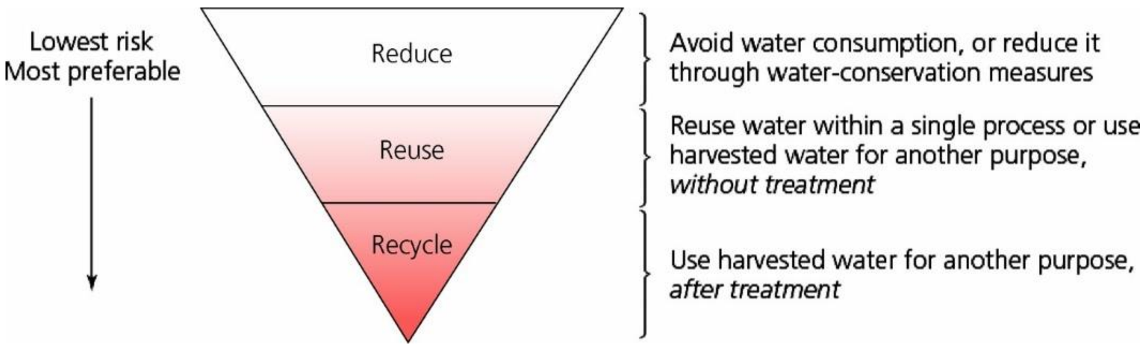


Figure 2-4 Water conservation hierarchy (Burns, 2016, p. 95)

Thus, water conservation can be defined as a process of minimisation of waste and loss combined with care, preservation and protection of all water resources to use water more efficiently (Butler and Memon, 2006). Undertaking this strategy has been an effective factor in reducing water consumption in buildings on an end use basis. Reducing the amount of consumed and waste water could make a considerable difference to water availability without taking more from the environment or reducing the level of service to consumers (DWAF,1999a). According to UN-Water (2021), there is a clear improvement in water-use efficiency worldwide, as demonstrated by the global increase of about 9% between 2015 and 2018, Figure 2-5. This could be interpreted as a result of more stringent water regulations that encourage people to save, reuse and recycle water.

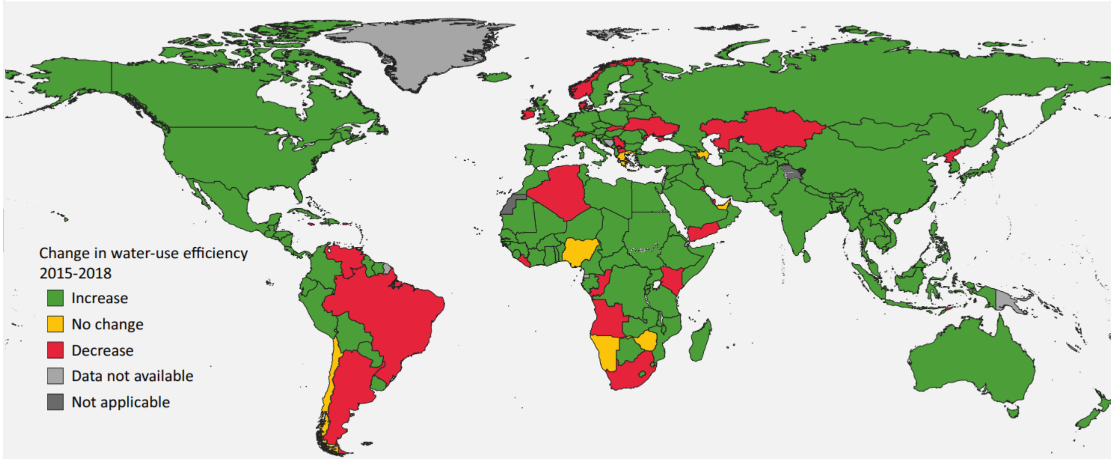


Figure 2-5 Global change in water-use efficiency between 2015 and 2018 (UN-Water, 2021)

In the UK, the increasing number of people alongside addressing the impacts of climate change have been the main challenges regarding providing adequate clean water for the population. The safe and economic exploitation of water along with water conservation and recycling potential in the UK could be promoted with more inter-disciplinary and inter-agency collaboration, building on the drivers outlined above, with everyone working together to reduce the various barriers. Additionally, water conservation is increasingly seen as part of the 'green credentials' of a development (Butler and Memon, 2006). The rise of general environmental awareness is helping to make clients increasingly prepared to pay a 'green premium' for conservation and recycling schemes in their developments. The water resources long-term planning framework from Water UK, published in 2016, stated that a twin-track approach of reducing demand and increasing supply is needed to secure the resilience of water supplies over the next 50 years as preparation for a drier future (DEFRA, 2018). Thus, using water-efficient appliances as part of water conservation planning is often associated with water saving as less water needs to be extracted, treated, transported.

2.3.1 Regulators and the government drivers

Greater public demand for water and the impacts of climate change have highlighted the need to address short-term problems and put in place medium- and long-term strategies to accommodate these trends. The limiting of ground and river water abstraction through the licence system is also driving companies to optimise the efficient use of available water. On the supply side, there is a need to capture, transfer and store more rainwater, while, on the demand side, it is necessary to reduce leakage, and conserve and use water more efficiently (DEFRA, 2018). The Government intends to work with stakeholders over the long term to encourage structural reform in the water industry including a significant increase in the uptake of water conservation and reuse, while supporting practical short-term local solutions on the ground, particularly in problem hot spots. As always, the government has attempted to balance stakeholder requirements, including those of the environment, customers and the water industry.

The UK Government has thus committed to Sustainable Development in different guises through, for example, the Agenda for Action 1996 using the Twin Track Approach and the Statutory Instrument 2004 No. 641 (c.24) of the 2003 Water Act that came into force in 2004 (Butler and Memon, 2006; DEFRA, 2008a). In addition, in A Green Future: Our 25 Year Plan to Improve the Environment (2018) the government stated its commitment to water conservation strategy as part of the overall goal of ensuring plentiful and clean water (HM Government, 2018). Furthermore, the UK Water Efficiency Strategy (2017), developed by Waterwise with collaboration of a wide range of water regulators, companies, businesses and customer groups, is an initiative aiming to raise ambition and delivery on water efficiency in the UK (Waterwise, 2021).

Local authorities are another driver of water conservation which manage water related projects during periods of flooding or drought. Local authorities are usually responsible for enforcing water supply regulations, often in conjunction with local water utility companies, to maintain and improve quantity and quality considering environmental protection. Water companies, meanwhile, are considered to be at the coal-face of water conservation. They are increasingly concerned about rising demand for water which in some scenarios appears unsustainable. A report by Ofwat revealed that tackling household leaks and using innovative technologies could help to decrease water use by two thirds over the next 50 years (R. Lawson, D. Marshallsay, D. DiFiore, S. Rogerson, S. Meeus, 2018). In addition, the Market Transformation Programme introduced by the government to support the use of sustainable products identified potential water savings of 10% from appliances such as WCs, taps, showers and baths (DEFRA, 2008a).

In the UK, therefore, the regulations are regularly reviewed with the aim of providing water supply systems that are sustainable and efficient. For instance, changes to Part G of the Building Regulations (2010) for England and Wales introduced a requirement for all new buildings to meet minimum water efficiency standards of 125 *l/p/d* (The Building

Regulations, 2015) . In Scotland, meanwhile, free water saving packs have been provided by Scottish Water and Home Energy Scotland to encourage citizens to use water wisely and reduce water consumption at home. This pack includes a range of devices to reduce water consumption, such as universal plugs, aerated shower heads, timers, kitchen tap aerators and cistern bags. Taking positive steps to use water wisely can make a big difference by not only saving water but also saving money and energy and reducing CO_2 emissions.

2.3.2 Environmental issues

There is clear scientific evidence that the climate has become warmer, and weather patterns have changed worldwide. According to climate change predictions, extremes of climate will occur more frequently in future than in the past century, with wetter winters but considerably drier summers. Over the last few decades, parts of the UK have experienced many severe droughts, especially between 1988 and 1992, and in 1995 (POST, 2000). The experience of summer 2018, where daytime temperatures consistently exceeded 30ºC for six weeks, reinforces the need to make our water supplies more resilient to a warmer climate (DEFRA, 2018). In July 2021, Public Health England (PHE) issued a heat-health alert, which was supported by the Met Office, as a result of rising temperatures in England (Publlic Health England, 2021). In Scotland, recorded rises in average temperature of 0.9ºC between 1961-1992 and the 2000s can be considered as evidence that climate change is affecting this area as well (SEPA, 2019a). At the same time, winter precipitation is predicted to increase for all periods and for all climate change scenarios (Hulme *et al.*, 2002; Roaf, Crichton and Nicol, 2009). This increase was predicted to be from10% to 35% depending on the emissions scenario chosen. Contrastingly, the summer pattern may become drier across the whole of the UK, with a decrease in precipitation of 35% to 50%. Summer temperatures in England are likely to increase by the 2050s, while summer rainfall will decrease, leading to an increased risk of short-duration droughts (DEFRA, 2018). The greatest changes in precipitation in both summer and winter are predicted for eastern and southern parts of England, while changes will be lowest in the northwest of Scotland. In general, there will be much more rain in winter, with higher intensity events inevitably leading to much higher flood risk, while conversely there will be significantly drier summers and more frequent droughts.

These changes will impact water availability and quality in different ways including reducing water availability during drought periods, higher pollution of water resources during flooding and drought periods, and long term depletion of ground supplies (Butler and Memon, 2006). In addition, water has to be used in an environmentally sustainable way in order to optimise its social and economic benefits. In some parts of the country, the amount of water taken from the environment causes damage to our ecosystems. The Water Industry National Environment Programme states that over 700 million litres per day (*Ml/d*) of abstracted volume needs to be cut by the water companies to address environmental problems and mitigate damage to ecosystems (DEFRA, 2018). In Scotland, the first national water scarcity plan was set out in 2020 as preparation to deal with water scarcity now and in the future. The aim of this plan was to work with users and key organisations to manage water resources during low rainfall periods. It is based on the premise that users have a significant role to play in using water sustainably and reducing the potential impact on the environment (SEPA, 2020).

2.3.3 Demographic considerations

Increasing household numbers and changes in lifestyle generally affect water consumption. Socio-demographic variables such as age and income level can also influence water demand (Willis, Stewart, Giurco, Talebpour and Mousavinejad, 2013). The issue of rising demand for water can be addressed by increasing supplies, however at the same time it is also important to emphasise demand management and securing a sustainable water supply. One essential step of this action is the support for more efficient use of water in buildings (POST, 2000). The population of the UK is predicted to grow by 5.5% from an estimated 65.6 million in 2016 to 69.2 million in 2026, with a trend towards smaller households using more water per capita and with more people living in urban environments (Office for National Statistics, 2017). The population in England is estimated to grow by over 10 million people by 2050, with a large part of this growth happening in areas where water is already scarce (DEFRA, 2018). The pressing need to provide drinking water for new developments will increasingly drive the move towards decreasing overall water consumption and looking at inventive ways in which adequate clean water supplies can be provided in a future where surface water and groundwater supplies may be less dependable than they were in the last century (Butler and Memon, 2006). Increasing water demand is likely to continue over the next two decades as a result of changes in lifestyle and buildings' occupants. This is because domestic demand falls into two main parts: demand related to the house which remains almost constant and demand related to occupants which varies depending on the number of users. One study from 2013 investigated the impact of family size on individual water consumption and the results showed that there is a typical reduction in water consumption per person when family size increases (Willis *et al.*, 2013). This means that despite a household of, for example, five people, using more water than a household of two, at the per capita consumption level, the household of five will have less individual water consumption. Thus, in the UK, given demographers' prediction of considerably smaller family sizes by 2025, water demand will increase, even if there is no change in the total population (McDonald *et al.*, 2015).

2.4 Water demand concept at building scale

It is important to provide adequate water supplies for different types of users, such as for domestic purposes, agriculture, industry and the environment, and to manage available water resources in the most efficient and equitable way. Information about water demand is required to design water and wastewater infrastructure such as pipelines, treatment plants and storage. Water engineers therefore need to know the water requirements of all types of users, where inaccurate water demand estimates result in either underestimation, which leads to insufficient system and inadequate service provision, or overestimation, which results in inefficient systems (Ilemobade *et al.*, 2010). Additionally, accurate water demand estimation is essential to help water utilities in developing successful plans to meet the needs of growing populations. Water utilities organisations must also enhance their water resource management and related infrastructure, including the repair and/or replacement of aging infrastructure (Danilenko, Dickson and Michale, 2010). Thus, water utility companies require updated information on water demand to operate treatment plants properly and meet both current and future demand. At the same time, they also require clear estimates of future demand across a timescale of around 20-30 years, to maintain and expand their treatment plants and/or develop new water sources (Donkor, Mazzuchi, Soyer and Roberson, 2014). More importantly, the estimation of water demand can be defined as the first stage of designing water pipe networks, storage, boilers and booster pumps in buildings. Parameters such as maximum flow rate or peak water demand are essential for the design of water distribution systems inside and outside buildings (Pieterse-Quirijns *et al.*, 2013). During sizing, designers firstly use design flow rate, and then assign reasonable values of design parameters and analyse the system using a trial and error approach to check whether the requirements of the system are satisfied

(The Institute of Plumbing, 2002; BS EN 806-3, 2006; BS 6700:2006+A1:, 2009; BS 8558, 2015; Aklog and Hosoi, 2017).

2.4.1 Per capita water consumption

Per capita consumption of water for domestic purposes varies from country to country depending on several factors including climate, technological advancement, availability of resources, legislative provisions and water price structure. Figure 2-6 shows the per capita consumption in different countries, with the upper extreme of 300 litres per person per day (*l/p/d*) in the USA and the lower end of 4-30 *l/p/d* in countries such as Zambia and Nigeria (Butler and Memon, 2006). Water demand level also varies significantly from household to household depending on socio-economic factors and household characteristics such as household size, type of property, age of household residents and time of year. Per capita consumption varies even in developed countries from 100 to 300 litres per person per day. The USA is at the top of this table, whilst the Netherlands and Germany are lower users (McDonald *et al.*, 2015).

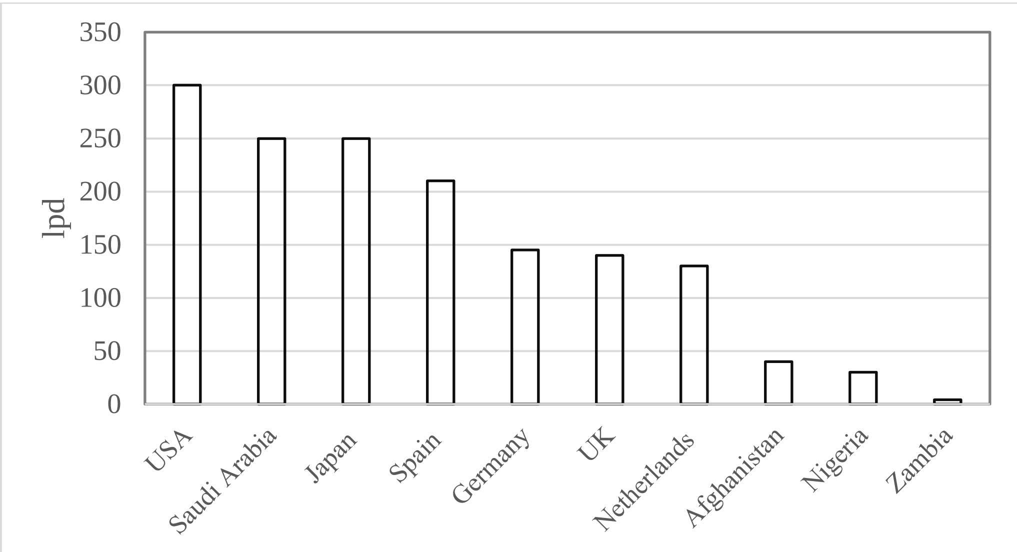


Figure 2-6 Per capita domestic water consumption in different countries (Butler and Memon, 2006)

A detailed study of water consumption in UK homes was published in 1978 (Thackray, Cocker and Archibald, 1978). This study provided basic information about household water consumption which had been unavailable previously, aiming to improve water demand forecasts in buildings. The per capita water consumption figures shown in Figure 2-7 and Table 2-1 present the study data for Malvern and Mansfield in England.

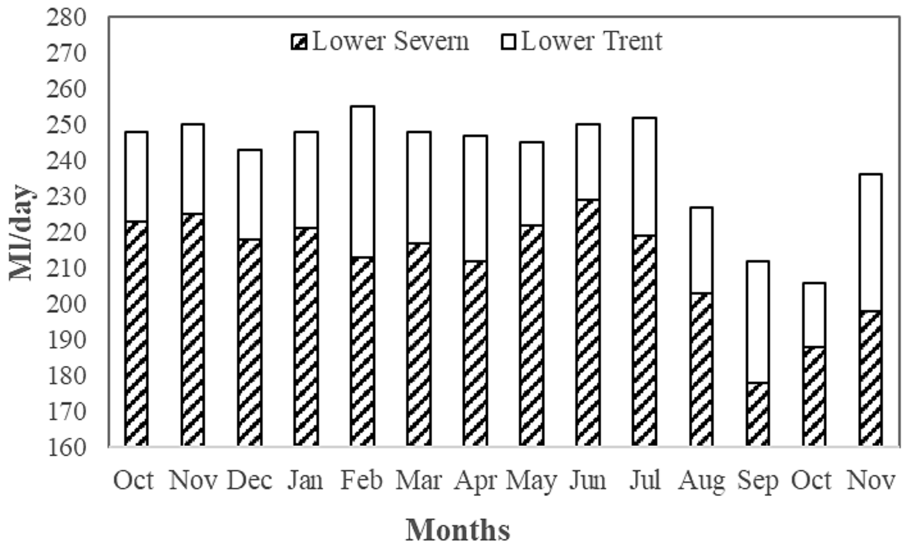


Figure 2-7 Monthly consumption in Malvern and Mansfield, Oct. 1975- Nov. 1976 (Thackray et al., 1978)

Table 2-1 Average water consumption in Malvern and Mansfield (Thackray et al., 1978)

	l/person per day	l/household per day	Average household size
Malvern	97·7 (2·3)	304·6 (8·9)	3·1
Mansfield	98·2 (2·6)	331·0 (10·7)	3·3

Over the years, there has been a reduction in water consumption in the UK, with Figure 2-8 showing how per capita water consumption decreased from 150 to 140 *l/p/d* between 1999 and 2018. Minimum water efficiency standards were introduced into the building regulations in 2010 which require all new homes to be designed so that their calculated water use is no more than 125 *l/p/d* or 110 *l/p/d* where an optional requirement applies (DCLG, 2014; The Building Regulations, 2015). In many cases, developers can achieve a reduction in water demand at little cost. For example, requiring developers to build to the lower standard of 110 *l/p/d* would only cost an additional £9 per dwelling (DEFRA, 2018).

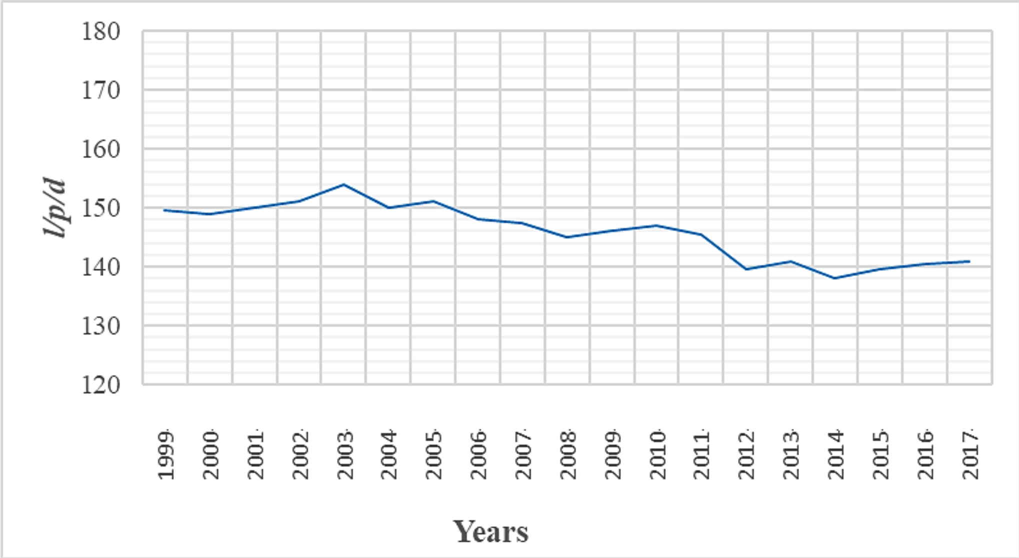


Figure 2-8 Per capita water consumption over time in litres per person per day (DEFRA, 2018)

2.4.2 Water demand end uses (Micro-component)

Investigation of water end uses has been used to assess different alternatives available to reduce water demand in buildings. It is helpful to know which sanitary appliances or activities are responsible for the greatest water demand in a building. Most of the research worldwide on estimating water end uses has focused on residential buildings, in such as the UK (Thackray *et al.*, 1978; Bradley, 2004), Spain (Gascon, Arregui, Cobacho and Cabrera, 2004), Brazil (Ghisi and Ferreira, 2007; Ghisi and Oliveira, 2007), and the USA (Deoreo, Mayer, Dziegielewski and Kiefer, 2016). For instance, in the USA, water consumption patterns for single-family houses were studied over two years in 12 different cities located in different climatic regions. Toilet flushing was the largest indoor use of water in these single-family homes, followed by faucets, showers, clothes washers, leaks, bathtubs, other/miscellaneous, and dishwashers, Table 2-2, (Deoreo *et al.*, 2016).

Table 2-2 Indoor household use by appliances

Toilet	Shower	Faucet	Clothes Washer	leak	Other*	Bath	Dishwasher
125 lpd	106 lpd	100 lpd	86 lpd	64 lpd	20 lpd	14 lpd	6 lpd
24%	20%	19%	17%	12%	4%	3%	1%

***** *The "Other" category includes evaporative cooling, humidification, water softening, and other uncategorised indoor uses.*

In the UK, a detailed study on water end uses in houses was published in the 1970s (Thackray *et al.*, 1978). Since then, many studies have been carried out to estimate the water end uses in all kinds of buildings. An annual Survey of Domestic Consumption (SoDCon) was undertaken by Anglian Water to investigate domestic water consumption patterns. This study included water consumption measurements for about 3000 houses in the eastern England region, with the focus on monitoring every appliance and water usage activity in 10 houses. Figure 2-9 shows the average water usage in the homes between 1993 and 1998. The results show that personal hygiene (WCs, baths, basins and showers) accounts for the highest usage, 60%, followed by washing machines and dishwashers at 21%, kitchen taps at 15% and outside taps at 4% (POST, 2000).

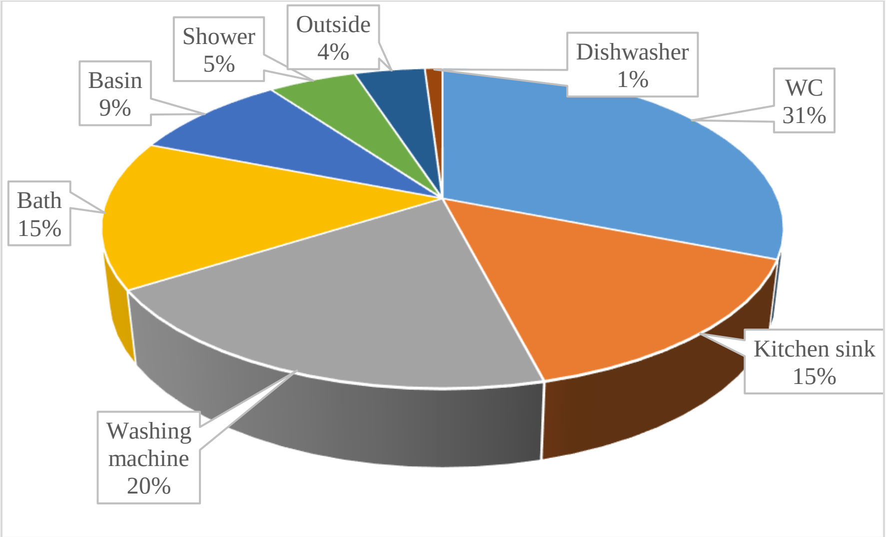


Figure 2-9 Average water consumption of different micro-components (Butler and Memon, 2006, p. 8)

In relation to non-residential buildings, some studies have been undertaken that address the issue of water savings, for example, studies to understand possible savings in institutional and commercial buildings in the United States (Dziegielewski et al., 2000) and one to estimate the main water end uses in office buildings in Brazil (Proença and Ghisi, 2010). With relevance to the research presented herein, to collect information on water activities and to identify the main end-uses, Proença and Ghisi (2010) investigated water usage in ten office buildings in Florianópolis, southern Brazil. This was achieved by interviewing the residents and observing flow rates. The frequency and duration of daily use for sanitary appliances such as WCs, taps, and showers were recorded from interviews, while the demand flow and appliance flow rates were obtained from site measurement. The data was validated by comparing with measured flow rates recorded by local water utility companies. This study also attempted to identify the best methods for potential water saving in office buildings. The results showed that the WC was responsible for the main water consumption, accounting for 52–84% in all the case study buildings, whereas water taps ranked second in seven buildings, with other results shown in Figure 2-10 (Proença and Ghisi, 2010). In the UK, water usage data on different sanitary appliances in office buildings presented in CIBSE Guide G (2014) identified the WC as having the highest indoor usage, Figure 2-11. The obtained results in these studies show that the WC has considerable impact on demand flow in office buildings and should, therefore, be carefully considered in water demand modelling.

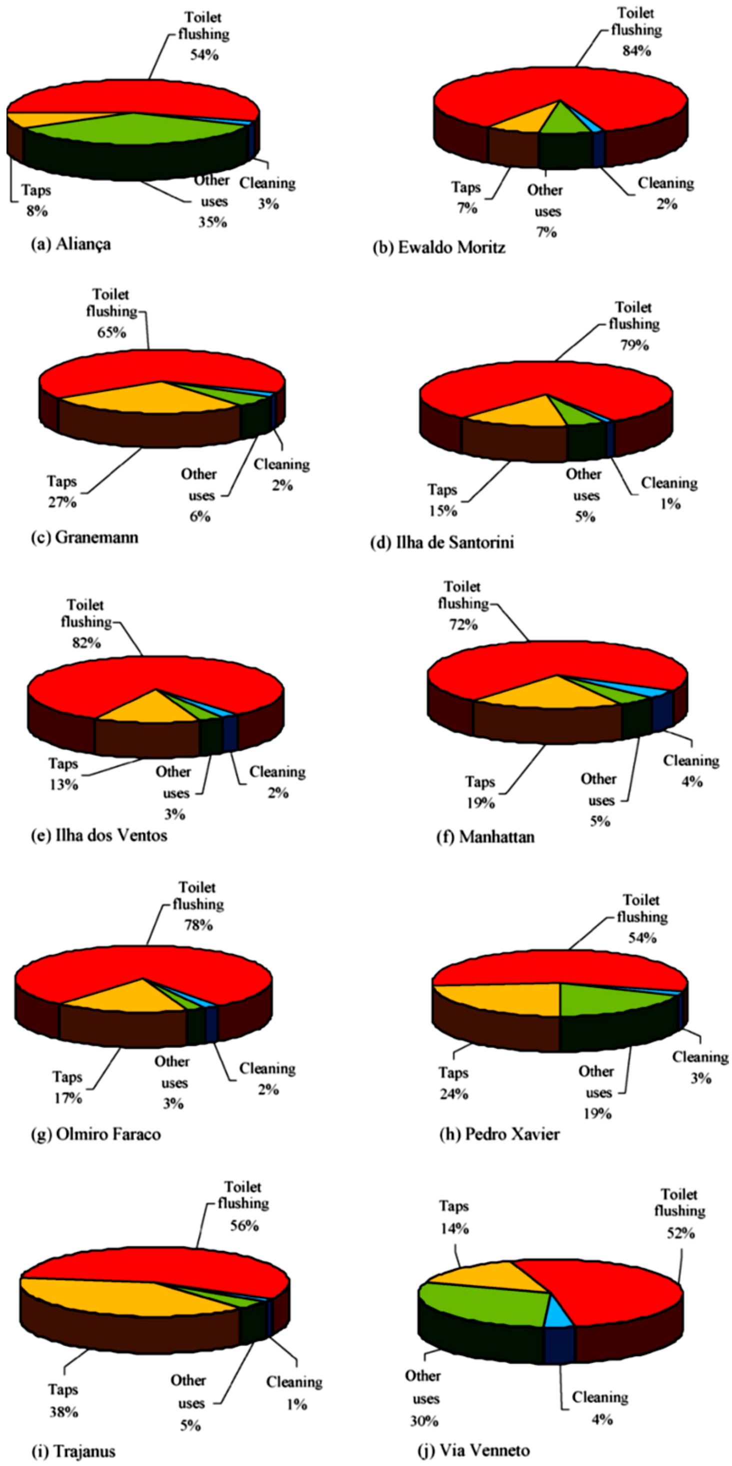


Figure 2-10 Potable water end uses for ten office buildings in Brazil (Proença and Ghisi, 2010)

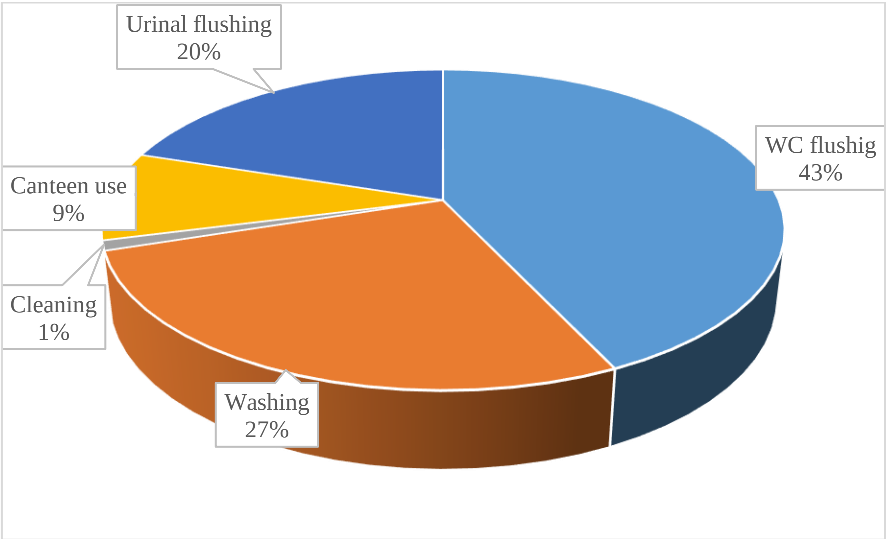


Figure 2-11 Typical water usage for offices (CIBSE, 2014)

2.5 Estimation of water demand in buildings

Water demand analysis is becoming increasingly important for utilities companies in order to ensure they can optimise delivery. Water supply systems are designed to transport clean water from a water treatment plant to buildings to be used by consumers for drinking, cooking, to ensure sanitary conditions and for other water activities. Of no less significance is the need to provide water for industry, business and for fire hydrants to maintain a sufficient level of public fire protection. Additionally, water supply systems may be responsible for the provision of water for other sectors such as recreation and parks, street cleaning and commercial uses. Thus, the design of water supply systems should meet two main requirements: first, it should deliver an adequate volume of water to meet consumer demand, and secondly, the supply should be reliable, i.e. able to provide a sufficient amount of water at all times (Hickey, 2008). In the context of supplying drinking water, two categories of pipe systems apply: i) Distribution pipes; a vast collection of large interconnected pipes transporting water from the treatment plant to the end user's property and which are usually buried, looped and maintained by a water utility company. In many cases, the dominant design consideration for distribution pipe networks is the "required fire flow" during a period of maximum daily water demand. In other locations, achieving self-cleansing velocities may be the main factor affecting pipe size in this system; ii) Service pipes; peripheral plumbing systems (pipes, meters, valves, connections and other appendages) that extract water from the main distribution pipes and convey it directly to the end user and which usually tend to be exposed, branched and maintained by the individual end user. End users typically are public or residential, commercial, industrial and institutional (Hickey, 2008; Buchberger *et al.*, 2012). This study focuses on the challenge of estimating peak water demand in main service pipes in buildings, with a particular emphasis on addressing the overestimation by current design guides used in the UK.

2.5.1 History of design of water systems

The basic requirement of any water supply system can be defined as providing high quality potable water for consumers at an appropriate flow rate at all points at all times. Design of the piping system in a building must meet this condition while also considering energy efficiency, sustainability and public health. The key concept underpinning this is accurate estimation of demand for water (Ingle, King and Southerton, 2014). In addition, water use activities indicate the daily habits of the building's residents. Most buildings have a diurnal water use pattern with different hours of high or low water usage. Peak hours that result in maximum flow rate can be considered as most important for designing water systems in buildings (Omaghomi and Buchberger, 2014). With the increasing size of buildings, estimating demand flow becomes more complicated because of unpredictable and fluctuating numbers of users in buildings. This issue was investigated for the first time during the 1930s by Dr Roy B. Hunter who was a research physicist at the National Bureau of Standards in the USA. Hunter used principles of probability to produce a single chart (Hunter's Curve) for predicting the design load of any combination of end users (more detail is given in the next section) (Hunter, R, 1940a). Since the 1940s, most design approaches used by engineers worldwide have been based upon improvements of Hunter's work, although the more recently-added label, "LU", is generally used in preference to 'fixture unit'.

Hunter's approach was widely accepted and is still used as a design method in most plumbing codes worldwide, including the UK. In the 1960s, Harry Howick, past-president of the Chartered Institute of Plumbing and Heating Engineering (CIPHE), previously the Institute of Plumbing (IoP), introduced a LU system based on Hunter's concept. This specified, for all appliances, a corresponding value of flow rate for the 'base appliance' which helped to simplify the application of the probability principle. This approach can be seen in the CIPHE design guide where an appliance (e.g. washbasin) with a frequency of use of once every 1200 seconds has been considered as the 'base appliance' having one LU, with all other sanitary appliances assigned a relatively larger value. This hence provides different LUs for the same appliances depending on frequency of use (Whorlow, 2016). In 1964, Howick adapted Hunter's approach to UK practice and introduced this method to the British Standard Code of Practice 310 drafting committee; it was then included in the 1965 version of this Standard (BS CP 310). BS 310, as a globally recognised and much respected design guide, became the basis of many of today's design guides (Ingle *et al.*, 2014; Whorlow, 2016). In 1987, the first edition of the British Standard BS 6700 was prepared under the direction of the Building Services Standards Committee and replaced CP 99, CP 310, CP 324.202 and CP 342. Since that time, the design guides have been occasionally updated in response to people's increased awareness of the need to save water and use water efficient appliances. Table 2-3 provides a summary of the most commonly used design guides in the UK (dating back to 1987) which all aimed to provide a better design approach in order to achieve an appropriate estimation of demand flow.

Table 2-3 Most common design guides in the UK between 1987-2021

No.	Year	Name
1	1987	BS 6700-1
2	1997	BS 6700 (Revised version)
3	2000	BS EN 806 - 1
4	2002	IoP
5	2004	CIBSE
6	2005	BS EN 806 - 2
7	2006	BS 6700 (Revised version)
8	2006	BS EN 806 - 3
9	2010	BS EN 806 - 4
10	2011	BS 8558
11	2012	BS EN 806 - 5
12	2014	CIBSE (Revised version)
13	2015	BS 8558 (Revised version)

2.5.2 Hunter's method

It is worth discussing Hunter's method here as thus established the first research in this field and the basis for most approaches that followed. In this method, Hunter suggested "fixture units" as a scale of numerical constants to assess water flow rates and hence determine pipe and storage sizes. He was able to calculate these units based upon the assumed interval between uses of a sanitary appliance, the time duration that the appliance would likely be in use, and the average flow rate. He chose those fixtures that had the most significant load-bearing effect on the water system for developing probability data, namely the flush-valve toilet, the flush-tank toilet and the bathtub. The loading data were dependent on these main factors for each type of sanitary fitting:

- the average flow rate during actual operation of the appliance (q),
- the average duration of flow for a single operation during opening an appliance (t),
- the time interval between successive operations of a given appliance (T),
- the probability that the appliance is busy (in operation) (p)

Water usage at a single appliance was described by Hunter as a Bernoulli trial with only two possible states: on or off. Thus, two time intervals were considered. Time considerations for successive operations were based on the assumption that the fixtures would be operating under congested service, i.e. there is more than one user for the same fixture. When one user is finished, another user begins, meaning that each fixture is continuously occupied. Different times were selected for the successive operation of each fixture, including five minutes for toilets and thirty minutes for the bathtub. Hunter recognised that his approach would result in an overestimation of design flow. He recognised that this does not originate from the application of the probability theory, but from a misrepresentation of the probability of simultaneous use of different types of sanitary appliances. In order to represent this simultaneous use, Hunter ingeniously applied a weighting concept as a solution in which two smaller curves were weighted relative to a bigger curve. This application was based on an arbitrary range from 1 to 10, and referred to as the fixture unit (Hunter, R, 1940a).

Hunter established his probability model to provide 99% satisfactory service, i.e. there is only a 1% chance that the actual demand load would be greater than the estimated peak load determined from the design chart. It is worth mentioning that this probability concept had already been applied to telephone exchanges in the USA to find their connection capacity. According to this model, the telephone exchange was allowed a failure rate of 1% , i.e. for one percent of the time, the exchange capacity would not allow further callers to be connected until other users ended their call. Application of a one percent failure was considered a fairly low failure rate and unnoticeable for the majority of the exchange users (Hunter, R, 1940a; Ingle *et al.*, 2014).

Thus, Hunter was able to standardise plumbing regulations in the United States and his publication, *BMS65 Methods of Estimating Loads in Plumbing Systems* (Hunter, R, 1940a), provided the industry with a design tool to estimate demand flow for a water supply network using "fixture units" for all type of appliances. Another publication by Hunter, *BM66 Plumbing in Manual* (Hunter, R, 1940b), set a global basis for code development and has been used in many countries worldwide.

Although Hunter's probability design factors can be defined as providing good engineering judgment for water use habits in the mid-1900s, since the early 1970s, debate over its application has increased among practising engineers and there has been a general understanding that this approach results in routinely and substantially over-sized water systems in buildings. This is because the factors have become outdated, especially since new legislation and regulations have mandated water-use reductions in plumbing fixtures. In addition, the existence of a wider variety of building types with different water usage patterns and water efficient applications requires a revision of the design chart. Several research projects have therefore been undertaken globally to enable a better estimation of design flow rate and reduce oversizing.

2.5.3 Most commonly used design guides in the UK (past and present)

There are now enough studies to confirm that almost all current design standards and guides result in an overestimation of demand flow in buildings; meanwhile, a brief review is useful to explain the methodology used to calculate design flow and to reveal the limitations and differences between them. Therefore, in this section the final versions of the standards and guides which have been used in the UK over the last few decades are discussed.

One of these design standards is BS 6700: "Design, installation, testing and maintenance of services supplying water for domestic use within buildings and their curtilages – Specification", which was published in 1987, followed by publication of a second version in 1997 and the last one in 2006. As at this time the installation of hot and cold water services in buildings was covered by an array of interrelated British Standard codes of practice, the main aim of producing this standard was to consolidate virtually all aspects of design for hot and cold water supply for buildings and their immediate surroundings but to exclude water treatment plants, water supply for industrial processes and fire-fighting systems. All three versions used the same loading unit table and conversion graph, Figure 2-12, except for the addition of loading units for domestic clothes or dishwashing machines (each with a LU=3) in the last version. This standard was withdrawn in 2011 after being replaced by BS 8558.

a)

Table 20. Loading units (hot or cold supply)

Appliances	Loading units
WC flushing cistern (9 L)	2
Wash basin	1½ to 3
Bath tap of nominal size ¾	10
Bath tap of nominal size 1	22
Shower	3
Sink tap of nominal size ½	3
Sink tap of nominal size ¾	5

b)

Loading units – Hot or cold supply

Type of appliance	Loading units
WC flushing cistern	2
Wash basin ½ – DN 15	1.5 to 3
Bath tap ¾ – DN 20	10
Bath tap 1 – DN 25	22
Shower	3
Sink tap ½ – DN 15	3
Sink tap ¾ – DN 20	5
Domestic clothes or dishwashing machines ½ – DN 15	3

c)

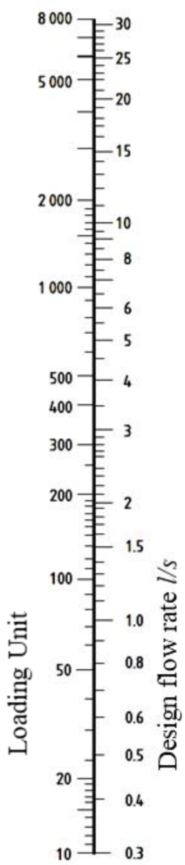


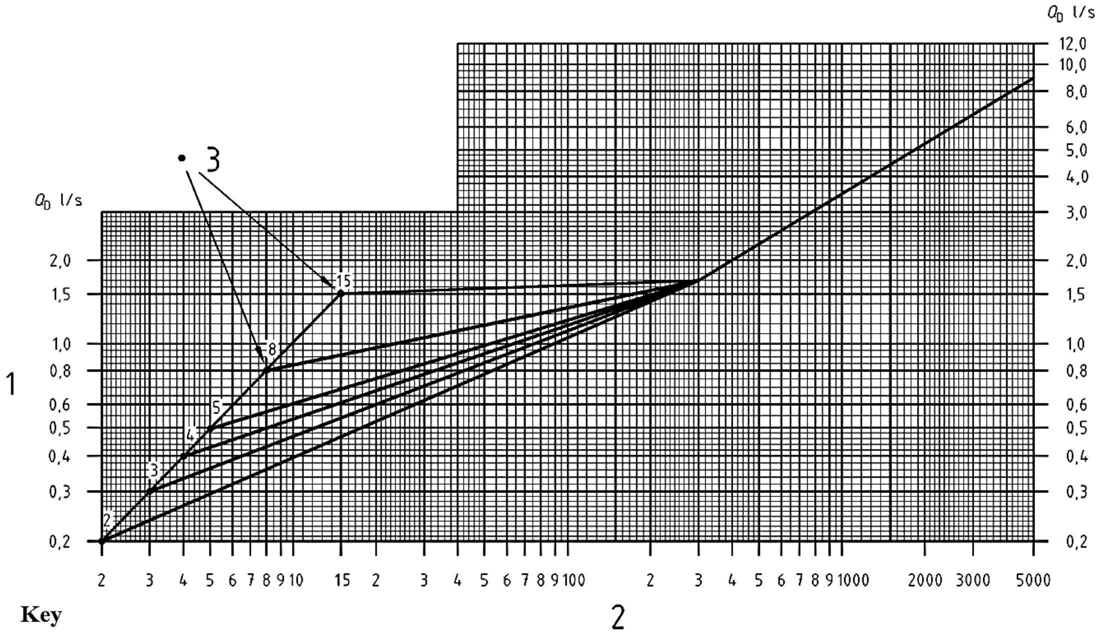
Figure 2-12 Determination of flow rates in BS 6700: a) Loading Units table (1987), b) Loading Units table (2006), and c) conversion of LUs to design flow rate

In 2000, the process of standardising the design guide for pipework systems in buildings within the European Union (EU) commenced with a new design guide, BS EN 806: "Specification for installations inside buildings conveying water for human consumption", which was published in five parts between 2000 and 2012. This European Standard was approved by the European Committee for Standardisation, CEN, and harmonised with the British Standard. In 2006, BS EN 806-3 was published. This described a calculation approach for the sizing of drinking water pipes in buildings and was recommended for use for residential buildings. BS EN 806-3 presents pipe sizing calculations for buildings and also outlines a simplified pipe sizing method for standard installations by assuming one LU to be equivalent to 0.1 *l/s* draw-off. The LU values are shown in Table 2-4 and a conversion chart is shown in Figure 2-13.

Table 2-4 Flow rates, minimum flow rates and loading units for draw-off point in BS EN 806-3

Draw-off point	Draw-off flow rates l/s	Minimum flow rates at draw-off points l/s	Loading units
Washbasin, handbasin, bidet, WC-cistern	0.15	0.1	1
Domestic kitchen sink, washing machine [a], dish washing machine, sink, shower head	0.2	0.15	2
Urinal flush valve	0.3	0.15	3
Bath domestic	0.4	0.3	4
Taps (garden/ garage	0.5	0.4	5
Non domestic kitchen sink DN20, bath non domestic	0.8	0.8	8
Flush valve DN20	1.5	1.0	15

[a] for non-domestic appliances check with manufacturer



Key

1 Design flow rate
2 Total flow rate in LU
3 Example of highest single value LU

Figure 2-13 Design flow rate in *l/s* for standard-installations in relation to the total flow rate in LU in BS EN 806-3

In 2011, BS 8558: "Guide to the design, installation, testing and maintenance of services supplying water for domestic use within buildings and their curtilages – Complementary guidance to BS EN 806" was first published. A new version was then published in 2015 which provided complementary guidance to BS EN 806. Thus, BS 8558:2015, as the latest British standard, confirms the withdrawal of BS 6700 and the recommended use of BS EN 806-3 for residential buildings. BS 8558 explains that care is required when assessing the combined demand of cold and hot water supplies in order to reduce the effect of oversizing. For sanitary appliances fed with both cold and hot water, the traditional loading unit model assumes that the system demand imposed by the appliance is met fully by each separate supply, which is logical when separate cold and hot water taps are fitted to an appliance. BS 8558 also states that this assumption is not valid when mixer taps or valves are used and it confirms that individual loading units relevant to the cold and hot water supplies ought not to be added together for sizing any combined cold and hot water demand. This point is the only difference between BS 8558 and BS 6700 as both use the same loading unit values and conversion chart to calculate design flow rates.

In addition to the British Standards, there are other publications which have no legal standing and are intended as guidance only. However, there may be a contractual obligation to follow them if they are referred to in project contracts. One design guide is the Plumbing Engineering Services Design Guide which was published by the Chartered Institute of Plumbing and Heating Engineering (CIPHE), previously the Institute of Plumbing (IoP). This guide was first published in 1988, and the latest version, which was issued in 2002, was enhanced to reflect the modern plumbing system. It provides more detailed guidance for the estimation of design flow rates using LU values; it was also developed from a probabilistic method and considers the period and frequency of use of each appliance. In addition, the water service section was expanded to include additional design considerations and to take account of the statutory requirements of the Water Supply Regulations 1999 in England and Wales, and the Water Byelaws 2000 in Scotland. It provides a range of LU values including three classifications of use: Low, Medium, and High, Table 2-5. The three groups are applied to reduce the effect of variations in capacity, flow rate, and period and frequency of use of appliances. A range of LUs makes the method more flexible and allows the designer to make professional decisions about choosing appropriate loading units. Low use is considered to correspond to 20 minutes between each use and is suitable for dwellings and other buildings where appliances are used by a single person or a small group. Medium use is considered to correspond to 10 minute intervals and is appropriate for buildings that are used by larger groups of people on a random basis and for which set time constraints are not required, such as public toilets. High use is considered to correspond to only 5 minute intervals as would be the case within buildings where the appliances are used by a large group of people over a short period of time, such as in theatres. After calculation of the total LU value, a conversion chart, shown in Figure 2-14, is used to find the corresponding design flow rate (The Institute of Plumbing, 2002).

Table 2-5 Loading units for draw-off points based on frequency of use in CIPHE

Type of appliance	LUs		
	Low	**Med**	**High**
Basin, 15mm sep. taps	1	2	4
Basin, 2 x 8mm mix. tap	1	1	2
Sink, 15mm sep/mix tap	2	5	10
Sink, 20mm sep/mix tap	-	7	-
Bath,l5mm sep/mix/tap	4	8	16
Bath, 20mm sep/mix tap	-	11	-
WC Suite, 6.litre cistern	1	2	5
Shower, 15mm head	2	3	6
Urinal, single bowl/stall	-	1	-
Bidet, 15mm mix tap	1	1	-
Hand Spray, 15mm	-	1	-
Bucket sink, 15mm taps	-	1	-
Slop Hopper, cistern only	-	3	-
Slop Hopper, cistern/taps	-	5	-
Clothes washing m/c, dom	2	-	-
Dishwasher m/c domestic	2	-	-

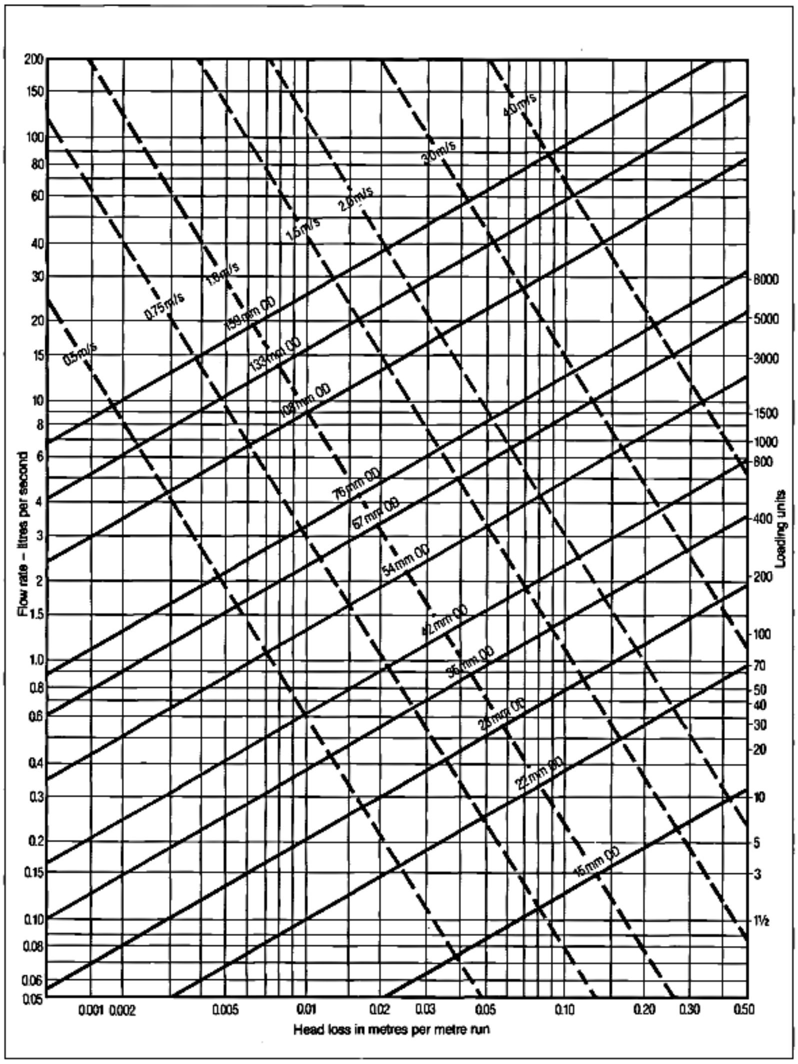


Figure 2-14 Conversion of loading units to design flow rate

Another guide in current use is CIBSE Guide G: Public Health and Plumbing Engineering (2014). The third edition was produced in collaboration between the Chartered Institution of Building Services Engineers (CIBSE) and the Chartered Institute of Plumbing and Heating Engineering (CIPHE) in 2014. This guide provides comprehensive guidance on the broad scope of public health engineering for all those involved in the design, installation, maintenance and specification of water and drainage systems. It covers water utilities and services, waste management systems, water treatment, conservation and sustainability, irrigation, etc. A part of this guide provides updated information on water demand estimation and pipework design to reflect new changes to water and sanitation standards in the UK. The guide also reproduces a probability graph to calculate the number of simultaneous appliances and loading units from CIHPE to estimate the design flow in buildings (CIBSE, 2014).

2.6 Scale of and reasons for the oversizing problem

2.6.1 Scale of overestimation of demand flow

In an attempt to assess the performance of current design guides and to improve the approach of demand flow estimation, different studies have been carried out to find the extent of oversizing worldwide. In Hong Kong, the fixture unit approach has been used as a design method for water demand estimation for sizing piping systems and water plant in buildings, based on an assumption of the probability of simultaneous use of outlets, along with an acceptable failure rate of 1% for design flow rate. A study showed that maximum demand flow in the water supply system is usually affected by simultaneous usage patterns of sanitary appliances as a result of users' behaviour and various architectural design features (Wong and Mui, 2008). Flow rate measurements from 1300 households in 14 typical high-rise buildings were used to determine parameters of a model and the results were compared with the theoretical design flow rates using the 'fixture unit' method. After comparison of the two data sets, it was found that the probable maximum water demand estimated from measured data was about half of that obtained from the 'fixture unit' estimation approach, which was considered as the current design method for determining water demand in residential buildings in Hong Kong, Figure 2-15 (Wong and Mui, 2008).

In Brazil, models were applied to apartment buildings to assess the design flow rate using the Monte Carlo method and the application of fuzzy logic. The Monte Carlo method assumes that water use is a random activity and it determines instances of use by applying a probabilistic formula, while duration of usage is determined from the application of fuzzy logic. The results showed that the design flow rate according to the Brazilian standard was about 23% greater than that obtained from the simulation (Oliveira, Cheng, Goncalves and Massolino, 2011).

In the Netherlands, studies were undertaken to assess the Dutch guidance on drinking water supply systems which depended on measurements obtained between 1976 and 1980 (Agudelo-vera *et al.*, 2013). For this purpose, Blokker et al. (2010 and 2011) developed a new procedure to determine peak demand flow based on a stochastic model called SIMDEUM (Simulation of water demand, an end use model). They found that the previous guidance generally overestimated the peak demand flow as a result of the increasing use of more water-efficient sanitary appliances available in the market and behaviour change among building occupants. The results showed that the new approach leads to better estimation of cold and hot demand flow than the old guides which resulted, for example, in overestimation of 70% to 170% in hotels.

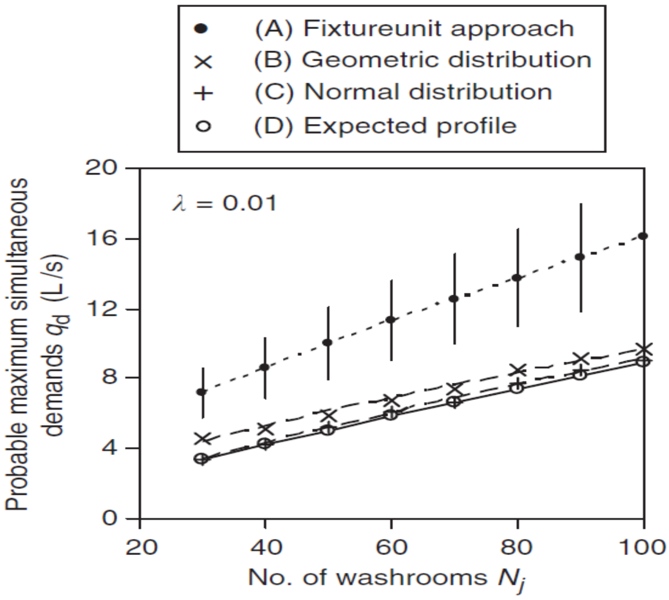


Figure 2-15 Probable maximum simultaneous demands of a number of sample domestic washrooms (Ilemobade *et al.*, 2010)

In the UK, as discussed in the previous section, there is more than one method for calculating demand flow rate and pipe sizing. In order to assess the existing British Standards, Tindall and Pendle (2017) used three methods: BS 6700, BS EN 806 and CIPHE, to determine the demand flow rate of domestic cold water services and then compared the results to measured data. Flow rates from direct measurement of two multi-storey buildings and from secondary data of seven buildings were used in the comparison. Design flow rates and observed flow rates for the nine case study buildings are shown in Figure 2-16. The results illustrate that BS EN 806-3 is the best method for predicting cold water demand because this yields a flow rate closer to that measured and less than that predicted by the other methods. Moreover, there was significant oversizing when BS 6700 was used, more than double the finding when CIPHE was used. The results confirmed that all design guides used in the UK result in over estimation for residential buildings. The authors were also able to show that even though BS EN 806-3 is the most accurate approach, it still results oversizing, by a factor of around two. Therefore, a new design method needs to be developed in order to obtain better estimation of design flow.

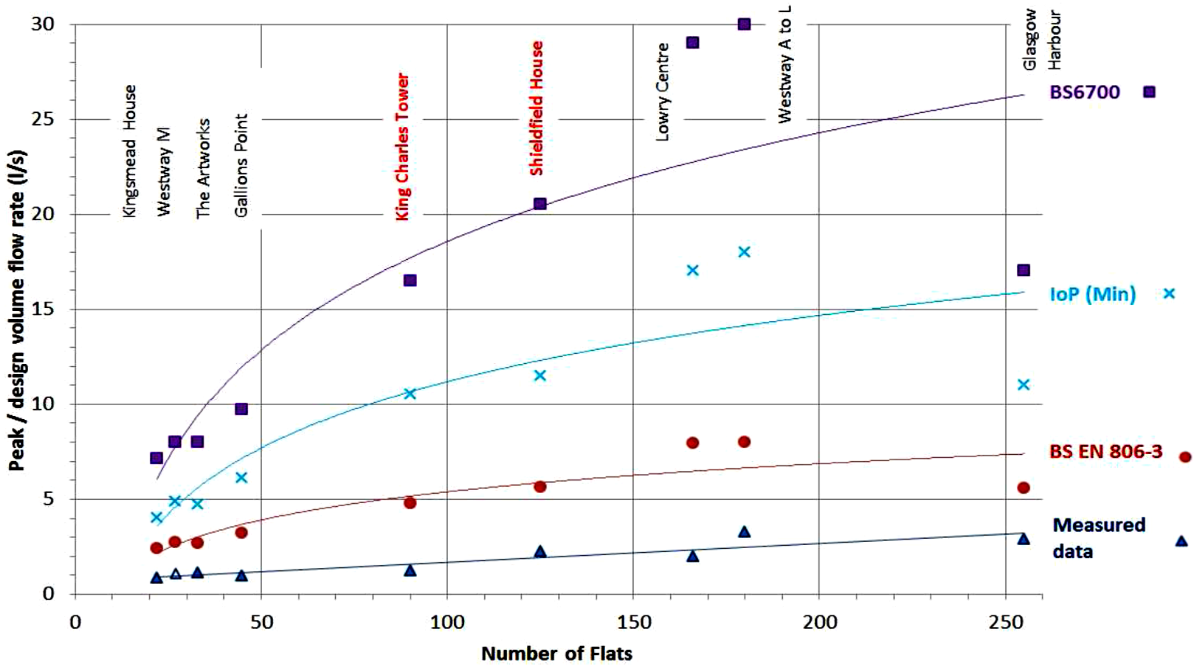


Figure 2-16 Design and measured flow rates for nine case study buildings

2.6.2 Reasons for oversizing

The current design guides generally result in overestimation of water demand. This is mainly because most of the design approaches use the "fixture unit" method derived from a probabilistic model to estimate water demand, all underpinned by the assumption that appliances are being used simultaneously in congested services in which there is a queue of users waiting to use each appliance, which often does not hold. In addition, the probabilistic approach uses mathematical parameters for the duration of use, for the fixture's flow rate and for how often the fixture is in use. Those parameters have changed considerably and water demand calculated for plumbing fixtures from the 1940s is not applicable to the new types of water conserving fixtures in modern plumbing systems. Furthermore, most of the design guides calculate design flow rate for a 99th percentile level of confidence, i.e. an acceptable failure rate of only 1%. However, there is no research to show the effect of one percent failure on the system or analysis of the performance of the system for this level of reliability.

In addition, there have been many changes in people's behaviour over the last few decades, including a growing environmental awareness and a willingness to engage with the environmental agenda. The main aim of demand management is to influence consumers to use water more efficiently by either implementation of metering, changing tariff structures, retrofitting or public awareness campaigns (Butler and Memon, 2006, p.

207). With provision of schools-based education on responsible water citizenship and information that will stand scrutiny, behavioural changes in using water have now permeated society. For instance, Ofwat published a focus report in 2011 (*Push, pull, nudge*) to investigate the role of water firms in keeping a balance between demand and supply to help their customers to save energy and water and reduce cost. The report also explained why the efficient use of water is important, and introduced three categories to encourage people to use water in an efficient way: push, pull and nudge; 'push' includes setting standards for water-using devices, including the regulations that apply to water fittings and new homes; 'pull' is about rewarding customers for using water wisely, such as charging customers for what they use; and 'nudge' is about considering consumer behaviour and using it to promote change, such as advertising and marketing to encourage consumers to change their water-use behaviours (Ofwat, 2011). In 2008, Defra published a framework for pro-environmental behaviours to improve understanding of consumer behaviour and attitudes. It included the motivations and barriers to individual and community action across a wide range of environmental problems. The framework aimed to help link water saving to other behaviours on energy, transport, waste, and environmentally friendly products (DEFRA, 2008a; McDonald *et al.*, 2015). In addition, working habits have changed, working hours have become more flexible and the changing ratio of men to women has caused a change of behaviour among water users (Pieterse-Quirijns *et al.*, 2013)

Furthermore, with the development of new technology over the last few years there has been a clear emphasis on water demand and saving water. In the 1940s, toilet cistern volumes were typically about 12 litres. The UK Government started to impose limits in the 1960s, and by the early 1990s, new toilets had a maximum flush of 7.5 litres. Now, a maximum flush of 6 litres has been specified by the water fittings regulations (Ofwat, 2011). Use of one water saving toilet by the householder leads to a reduction in water demand of 10-11% (Milan, 2006). Users are also encouraged to use water-efficient products through provision of appropriate forms of product labelling. The Water Using Products Group, facilitated by the Waste and Resources Action Plan (WRAP), worked with the Bathroom Manufacturers' Association, major retailers and merchants to encourage people to buy water-efficient products through the use of the Water Label (The Water Label, 2019). The Water Label provides comparative information on volumes of water use between similar appliances, thereby helping consumers to make an informed purchasing decision (DEFRA, 2014; Kelly, 2015).

Therefore, there is growing agreement among practising engineers that in most building types, the application of Hunter's method results in overdesign of the water supply system (The Institute of Plumbing, 2002; Wong and Mui, 2008; Buchberger, Omaghomi, Wolfe, Hewitt and Cole, 2015). The above reasons confirm the need to develop a new model with new parameters to reflect the modern water system considering both the remarkable change in people's behaviour and increased efficiency of water appliances.

2.7 Conclusion

Providing adequate drinking water to meet demand has become a challenge globally as a result of complex factors, such as population growth, climate change and environmental awareness. In sustainable building design, fresh water demand has been defined as one of the main concerns in terms of water resource management. Water demand management has a key role in addressing this challenge and water conservation has become a crucial element in managing the balance between supply and demand. Climate change, as an environmental challenge, has a direct effect on water availability where severe drought is predicted to occur more often for all climate change scenarios. With increasing environmental awareness, the amount of abstracted water should be minimised to avoid damage to our ecosystems. In addition, increasing population and changes in lifestyle are considerable drivers that impact water consumption. Understanding and addressing water use therefore becomes important not only to size water networks, but also to provide operational and strategic plans to meet current and future demand. Information on per capita water consumption and water end use (micro-components) provides important indicators of total water demand and informs us of which appliances or activities result in greatest water usage.

To use water more efficiently and meet demand in the future, water conservation planning has taken different forms such as reducing loss, using water-efficient appliances and raising people's awareness. Previous studies have confirmed that significant savings can be achieved through water demand management programmes and using water efficient appliances. As a result of using water more efficiently and awareness of the need to save water, flow rate at the end use point in buildings has been reduced. It is due to this reduction and the use of out-of-date design approaches that an oversizing problem has appeared in water supply systems.

In order to tackle this problem and to better estimate flow, the design guides and standards have been updated from time to time. However, all versions used the same loading unit approach that originated from Hunter's method and which was defined as the first approach for estimating demand flow in buildings. This approach provided a global basis for water demand modelling and has been accepted as a design guide in many countries since its first introduction in 1940. In light of growing concern among practising engineers and designers that the application of Hunter's method results in overdesign of the water supply system and does not reflect modern plumbing systems, the design guides have been updated and new studies have been undertaken to develop new design approaches. In the UK, different design guides and standards have been investigated to assess their performance in water demand estimation, with the evidence confirming that all result in overestimation of demand flow and oversizing of water supply systems. This study therefore focuses on developing a new model to estimate demand flow with new parameters to reflect the modern water system in buildings.

Chapter 3 Statistical models and illustrative methodology for developing a new model

3.1 Introduction

In general, there is international agreement that current design methods result in significant overestimation of simultaneous flow load for buildings (Blokker, 2010; Oliveira *et al.*, 2011; Buchberger *et al.*, 2017; Jack, 2017; Tindall and Pendle, 2017). Although using different techniques, statistical models underpin all methods adopted by design codes worldwide. Most international design codes have originated from either a probabilistic, empirical or stochastic approach. In the UK, while each sizing method makes different assumptions regarding LUs and the conversion from LUs to flow rate, all of these methods use the same fundamental LU approach. This chapter provides a critical review of the statistical foundation and recent approaches used to estimate water demand in buildings and explores the requirements for developing an alternative model. It presents a comprehensive analysis to reveal the functional elements that should be incorporated into any alternative model and identifies associated constraints. This section concludes by presenting scientific justification for using a stochastic model and elucidation of methods for determining model requirements. Definitions of the parameters necessary to develop a new stochastic model are discussed. This chapter concludes with decision making on the best options to define the input variables and apply them within the model.

Figure 3-1 presents an illustrative diagram of the project methodology and explanation of the following chapters. Firstly, the work introduces statistical models that could potentially be used to better estimate water demand and provides a critical assessment of each. Additionally, a systematic review is conducted of the main approaches recently introduced in studies worldwide in order to identify the most useful techniques for developing any new model (Chapter 3). Secondly, the development of a new model, the Water Demand Estimation Model, is explained in detail in conjunction with the derivation of the final design equations (Chapter 4). Thirdly, a description is provided of the process of gathering actual flow data required for validating the model and associated input variables (Chapter 5). Finally, the performance of the model is assessed by validation against measured flow data and through comparison of design, measured and simulated flow rates (Chapter 6).

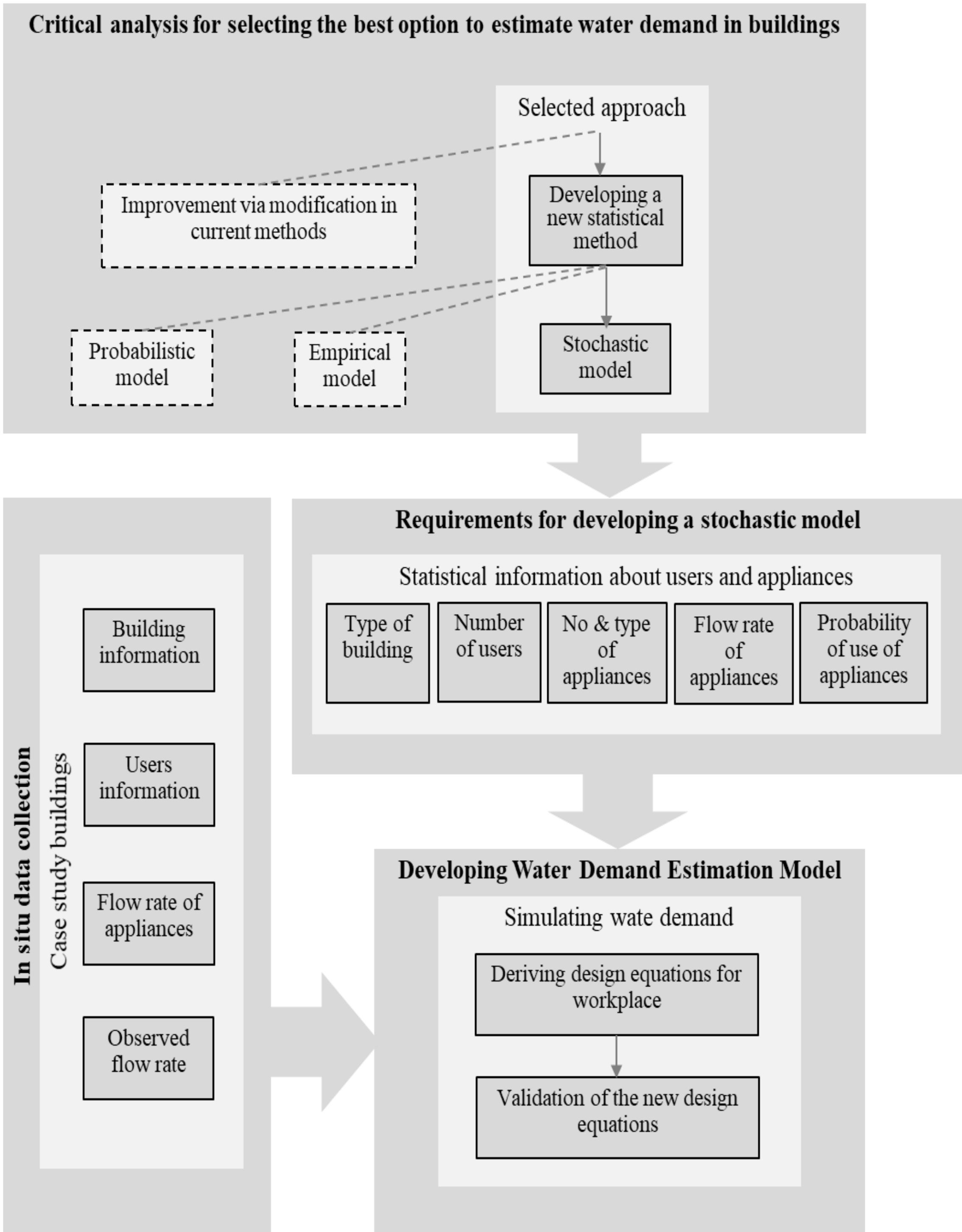


Figure 3-1 Statistical framework of the project methodology

3.2 Optimisation of estimating water demand in buildings

It is clear that inaccurate estimates of water demand may result in either underestimation, with inadequate service provision, or overestimation, producing inefficient systems with negative health consequences. Therefore, with changing lifestyles, new technologies and growing environmental awareness, many efforts have been undertaken to improve design approaches for application to the modern water system. In order to address these issues, there are two different directions that can be taken:

3.2.1 Modifying the existing design approaches

One direction is to continue with the existing fundamental design approaches originating from the Hunter method, but with some modification. This kind of modification can be achieved by updating the fixture unit values or adding new types of sanitary appliance. The main criticism of this strategic direction is that these modifications have often been made based on engineering judgement rather than on observable data, resulting in a disparity among fixture unit values between plumbing codes. Such modification, resulting in a substantial decrease in estimated demand, is seen in the National Standard Plumbing Code NSPC (2012), which was also partially reproduced with modifications to the Uniform Plumbing Code (UPC) for use in the USA. In the UK, design guides have been updated periodically and there are hence different versions of the codes, see Table 2-3 in chapter 2. Each version makes different assumptions regarding LUs and uses a different conversion chart to convert LUs to flow rate. One of the major modifications made in the British Standards was the introduction through BS EN 806-3(2006) of a new method for water demand estimation that assumed one LU to be equivalent to 0.1 *l/s* draw-off, which is significantly lower than in previous design guides. Reducing the value of the LU in this way resulted in a reduction in predicted water demand and enabled this guide to be recommended for use for residential buildings. Meanwhile, recent modifications in the design codes have had no significant impact on reducing the oversizing problem. For instance, Tindall and Pendle (2017) illustrated that updating the LU method without changing the original model cannot fully address the oversizing problem as all the design approaches suffer from serious limitations, primarily their use of the same LU underpinning. This confirms that any further modifications are likely to be insufficient, and emphasises the need to develop a new model with new parameters that can be effectively applied to the modern water system.

3.2.2 Developing new models

Numerical and stochastic models can be used as alternatives to the LU method for developing new approaches and making more accurate predictions of the simultaneous design flow rate in buildings. Since the LU method first came under scrutiny, there have been various attempts to develop an alternative approach. For example, a mathematical model was developed by Webster (1972) using experimental work with Newton's Binomial Theorem in which a failure rate of 0.1% was applied instead of 1%. Although the failure rate was ten times lower than that used by Hunter, the model still predicted a flow rate lower that those obtained from the LU method in British Stander Code of Practice 310. However, this method was not adopted in the UK and BS 310 remained the definitive design guide (Ingle *et al.*, 2014). In 1975, the American Water Works Association AWWA discussed the use of field measurements undertaken in the United States and Canada to derive a new family of curves. Mechanical data loggers were used to collect peak flow readings for a range of customers. A family of demand curves for several customer categories was created, including residential buildings, commercial buildings and public facilities. However, the findings derived by this method were based on a limited sample of customers and measurements were taken before the introduction of the 1992 EP Act (AWWA, 2014). More recently, the task of developing new models has been incentivised and made easier by the availability of new technologies and computer programs. For example, ultrasonic flowmeters allow measurements to be taken without the need for insertion of any mechanical parts through the pipe wall, and software can be used to analyse large data sets. Thus, different types of models have been developed. For example, SIMDEUM in the Netherlands and the Water Demand Calculator in the USA are being successfully used as alternative methods to calculate design flow in buildings.

3.3 Statistical models for water demand estimation

As the main aim of this study is to develop a new model to better estimate design flow rate, it is essential to critically assess all types of model and select the best option to achieve the goal. In the past, different statistical models have been used to predict water demand in buildings. However, these models differ in terms of their input variables, methodology, complexity and level of accuracy. In general, there are three types of statistical model, namely probability, empirical and stochastic models. All design codes use one of these statistical approaches and Table 3-1 shows examples of international codes and related types of model. Although research has been carried out on the probability method, the empirical method and data used in the models remain largely unresearched. Meanwhile, stochastic models have only been applied in the Netherlands.

Table 3-1 Examples of international codes and related statistical models (Jack, 2017)

Code	Country	Statistical Model
Code BS EN 806	UK	Probability
BS 8558 (BS 6700)	UK	Probability
CIBSE Guide G	UK	Probability
CIPHE/IoP	UK	Probability
IPC/UPC/NSPC	USA	Probability
ISSO - 55 (Code)	Netherlands	Empirical
ISSO - 55 (via SIMDEUM)	Netherlands	Stochastic
SANS 10252-1	South Africa	Empirical
UNE 149201	Spain	Empirical
DIN 1988-300	Germany	Empirical
DS 439	Denmark	Empirical
SNiP 2.04.01-85	Russia	Empirical

3.3.1 Probabilistic models

Probabilistic methods are based on assumptions and distributions of probabilities to derive mathematical expressions, tables and graphs. They can estimate water demand for sizing a piping system and water plant for a building using all outlets simultaneously and run at their design flow rates with an acceptable rate of failure (Hunter, R, 1940a; Wong and Liu, 2013). Probabilistic models, as the name suggests, use parametric probability distributions to determine the likelihood of possibilities of various numbers of appliances being in simultaneous use. This method relies on the fact that water use in a building reflects the daily habits of its occupants and the statistical nature of flow rates and sanitary appliances. It also considers an acceptable failure rate to give demand flow estimates for selected levels of performance (Wong and Mui, 2018). However, water usage can be defined as having a diurnal pattern in many cases, while different periods of high and low water use activity may result in different values of peak water demand. The random nature of peak water demand enables the design flow rate to be estimated and interpreted using the probabilistic concept.

Most probabilistic approaches are based on Hunter's methodology to estimate design flow rate in buildings. Hunter theorised that because the sanitary appliances in water systems are used intermittently, the demand flow must depend upon three design parameters: i) the average water flow rate of the appliance, ii) the average duration of time the appliance is in use, and iii) the time interval between successive operations of the appliance. Thus, a scale of fixture units was developed to estimate design flow rate using probability theory. In addition, an allowable failure rate was applied to this approach which allows an estimation of demand flow corresponding to a desirable level of performance. Hunter applied a 1% failure rate (Oliveira *et al.*, 2011; Jack, 2017). Since Hunter's approach was developed, the probability approach has set a global basis for code development and has been used by engineers and designers in many countries worldwide. Hunter's approach can be defined as a firm base of probability theory for estimating demand flow in buildings. As the method is relatively straightforward and the important factors are defined in a straightforward manner, the method has become widely embedded in most international design codes over the past 80 years.

As was discussed in section 2.6, there has been a general understanding that the probability approach routinely results in substantially oversized water systems, as has been confirmed by various studies. Consequently, research has been undertaken globally to develop an alternative model for better estimation of design flow. An associated shortcoming of the probability model is that various assumptions can lead to inaccurate results. These assumptions may include judgements or the selection of probability distributions. In addition, the fact that most probability methods were developed before the advent of powerful computer technology also detracts from the reliability of the outcomes. Although probability models may not require flow rate data, the accuracy of the model is extremely sensitive to the quality of the statistical data of the input parameters. Furthermore, this approach fails to take direct account of factors such as the number of users; an essential consideration in water demand estimation. Another disadvantage of the probabilistic approach is that it is restricted to a single outcome and its associated probability (99th percentile), provides less flexibility to the user and prevents the option to choose a preferred level of confidence during the design and decision making stages.

Despite the fundamental theories of probability having a role in most of the current design codes, there is no room for further improvement without developing a new model that addresses all the limitations to reflect 21st century plumbing systems. As this study focuses on finding a novel approach to estimate demand flow considering the changes in both people's behaviour and appliance efficiency, it chooses not to work on improvement of the traditional probability method, but to apply new techniques and computer simulations together with the essential probability theories to develop a robust model for water demand estimation.

3.3.2 Empirical models

Empirical models can be defined as much simpler in terms of set-up and application. For a given set of parameters, the model generates one possible result or solution. This approach is based on exploring the mathematical relationships between input and output data to derive formulae, tables and charts (Oliveira *et al.*, 2011; Jack, 2017). The efficiency of the model depends directly on the quality and quantity of the data. As the model depends on measured data, it may not involve any probability assumptions or theory. Depending on the underpinning data collection, it is possible that such models can be used for different building types.

However, while many standards for pipework sizing are based on empirical methods, there is little information on the data used for developing empirical formulae; neither is there any information on their statistical validation. Despite the simplicity and accuracy of empirical models, the major problem is that their usefulness in water demand estimation is limited by their short lifetime validity. Any change in parameters such as peoples' behaviour or appliance efficiency will have a direct effect on the performance of the model as it cannot be retrospectively updated without new data. Another weakness is that the model outcome depends directly on the quality and quantity of the data, with a large data set required to cover all types and scales of buildings. The model also requires high resolution (5-10 seconds) data to capture simultaneous uses of sanitary appliances; however, such data sets are not available in the UK and are challenging to obtain in terms of time, cost and accessibility. Another potential problem is that because this method uses actual flow rate data from direct measurement, confidence levels cannot be applied in determining the outcome of the model. The model therefore needs to be interpreted with caution to reflect the desired level of confidence. For the above reasons, an empirical model was not selected for use in this study.

3.3.3 Stochastic models

The stochastic process produces a particular type of model that represents the uncertainty in a dynamic system using the language of probability (Nelson, 1995). It is the traditional option to test scientific theories when processes, observations or boundary conditions are subject to stochasticity. Stochastic models offer a computational approach that establishes probability distributions that represent the uncertainty and randomness associated with a given set of input variables, Figure 3-2 (Hartig, Calabrese, Reineking, Wiegand and Huth, 2011).

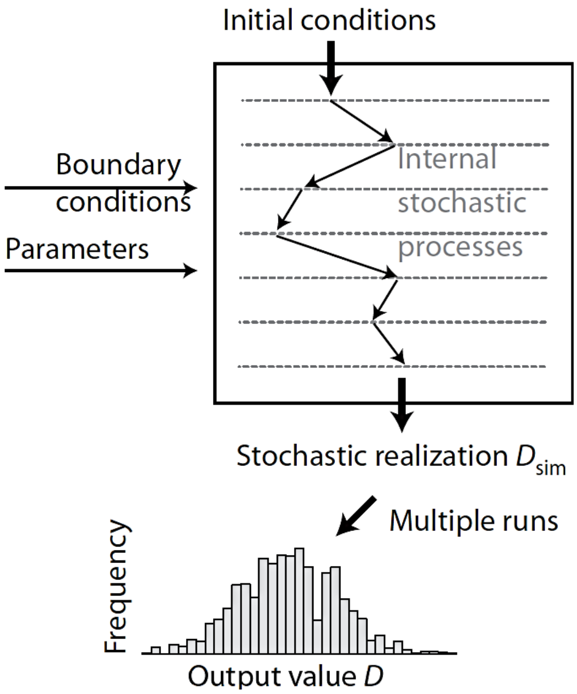


Figure 3-2 Illustration of stochastic simulation (Hartig *et al.*, 2011)

The outcomes rely on the modeller's ability to use appropriate modelling tools, correct assumptions and to address various coding challenges while managing large amounts of data. It is often necessary to develop additional tools in order to interpret the outcomes of the model in a meaningful manner. Despite these challenges, stochastic models can be used successfully to determine the maximum water demand in buildings. Blokker (2010) has shown clearly that a stochastic model can predict water demand to an acceptable level of accuracy. Stochastic models can also provide a strong base for deriving design equations for different types and scales of buildings. One of the main strengths of the stochastic model is that it can be developed without using flow rate data as it is based on statistical information on users and sanitary appliances; available before any information on water usage is collected. The ability to update and improve the model in terms of the input parameters renders it applicable to different types of buildings in different locations and adaptable to future changes. In addition, the outcomes of the model include a range of possible levels of confidence, allowing flow rate to be calculated for any desired level of reliability. These advantages justify the use in this study of a stochastic model to estimate design flow rate.

It is worth mentioning that all models in which fundamental probability theories are used can be defined as probability models. However, in this study, the WDEM can be described as a specific type of probability model, i.e. stochastic. This is because techniques such as Monte Carlo were used to create a boundary condition of stochasticity. Generating hundreds of thousands of probabilities of water usage events makes the model different from traditional probability models and enables the model to be described as a stochastic model. In addition, in the previous water demand estimation models, probability theories are commonly applied to determine the chance of occurrence of a specific water usage event, for example, the 99th percentile as design flow rate. However, in this study, the binomial equation is used to determine the number of busy appliances instead of the probability of the events, i.e. assuming probability to find corresponding busy appliances. The application of the Monte Carlo technique enables the model to generate a wide range of random data to capture all possible simultaneous usage of the appliances. The application of these techniques, therefore, makes the model distinct from traditional probability models and able to be described as a stochastic model.

3.4 Recent studies on demand flow estimation

It is essential to investigate and assess recent research in this area. This will enable the study not only to benefit from the strengths and avoid the weaknesses of previous approaches, but also to identify how new techniques along with dominant parameters should be applied.

Since the 1940s, the methods used to estimate design flow rate have been based mostly upon improvement and updating of the probabilistic model 'fixture unit' which was originally developed by Hunter (1940) in the USA. Previous studies have shown that looking for an improvement of the 'fixture unit' method is widely recognised as an outdated approach (Hobbs, Anda and Bahri, 2019). In the UK, the updating of 'Loading Units' in the British standard BS 806-3 is a good example to illustrate that improving the current approach may not provide an optimum response to overestimation of water demand. Developing a new model has therefore become the key driving force behind most studies in this area. Computational and stochastic models are the main developments in this field, boosted by advances in computer programming. The following text outlines three approaches which have been developed relatively recently in Brazil, the Netherlands and the USA. The reasoning behind selecting these three methods is their practical way of estimating design flow rate and the successful outcomes of the approaches.

3.4.1 Combination of Monte Carlo and fuzzy logic

Earlier methods used in Brazil to estimate design flow rate did not take into account the users' activities and building features. To address this issue and to achieve better performance and reliability of the approach, Oliveira *et al.* (2011) presented a simulation model for estimating design flow rate in water sub-metering systems that is based on probabilistic and possibilistic approaches. In this approach, flow rates in building water supply systems were linked to interactions between the user and the sanitary appliance, according to the following three factors:

> " i) *activities of the users: a function of the type of building (residential, school, hotel etc.) and of the characteristics of the users, which depends on physiological, regional, cultural, social and climatic aspects;*
>
> *ii) characteristics of the building: a function of the users (population and distribution) and of the spatial organization;*
>
> *iii) characteristics of the set of sanitary appliances: a function of the types and the amount of sanitary appliances"* (Oliveira *et al.*, 2011).

For this purpose, an apartment in the city of São Paulo was selected as a case study. Three residents participated in the study. For each person, a set of fuzzy logic principles was defined to represent shower duration and air temperature, Figure 3-3. Results from the research showed that the demand flow in the supply branch pipe was less than 0.17 *l/s* for most of the time, where this is significantly lower than the design flow rate of 0.42 *l/s*. After comparing the methods of calculating design flow, the results showed that the simulated flow rate was about 23% and 13% less than the demand calculated from deterministic and probabilistic methods, respectively (Oliveira *et al.*, 2011).

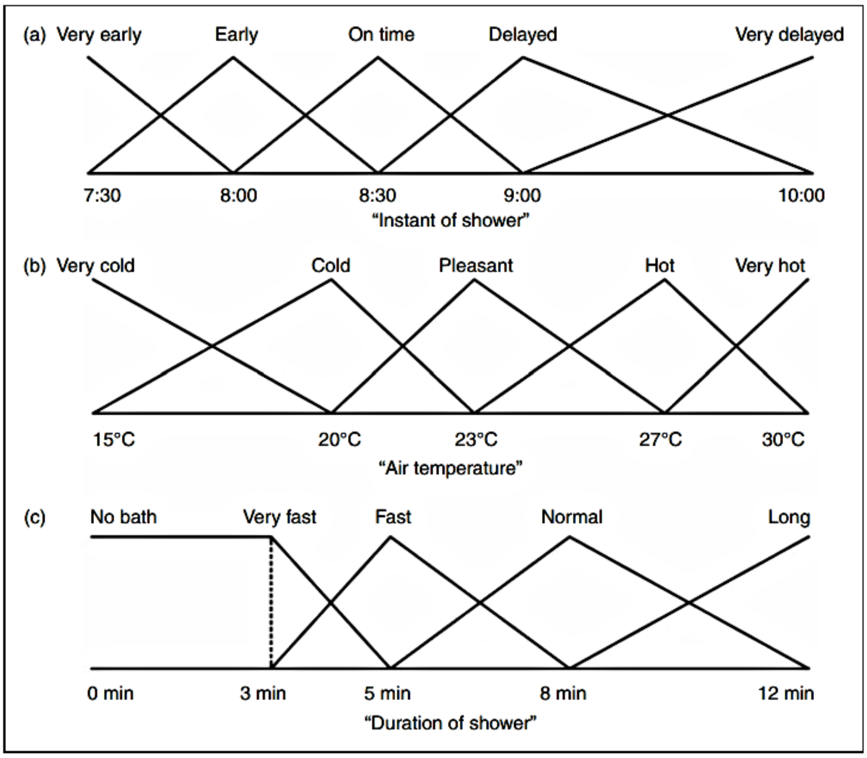


Figure 3-3 Linguistic values of the variables: a) instant of shower, b) air temperature, and c) duration of shower (Oliveira *et al.*, 2011)

Although the initial results of the study indicate that this is a useful example of a water estimation model with a clear reduction in design flow rate, the method has not been adopted within Brazilian design guidance as it is limited to water sub-metering systems for multi-family buildings. There are certain problems with the data used; some information in the data set was based on only three participants in a single flat, while a larger data set would be required to fine-tune the simulations for application to other types of buildings. In addition, considering only the shower in a fuzzy logic application and disregarding other appliances introduces limitations to wider applicability.

It is important to note that the findings from this study confirmed that the Monte Carlo technique played a key role in the simulation, in particular in identifying the use of sanitary appliances and their frequency. The results suggest that people's behaviour is another important factor in water demand modelling that should be considered in future research. This study also shows that consideration of user behaviour in a water demand model ideally requires the collection of qualitative data, which can be done through methods such as one-to-one interviews, focus groups, and observations.

3.4.2 SIMDEUM

The SIMDEUM (**SIM**ulation of water **D**emand, an **E**nd-**U**se **M**odel) approach has been used for the estimation of water demand in the Netherlands since 2013. SIMDEUM can be described as a stochastic model that is able to estimate demand flow at a short temporal scale *ie*. one second and spatial scale of a single building, for example, estimating demand flow in *l/s* for an office building (Blokker, 2010; Blokker, Vreeburg and Van Dijk, 2010; Blokker *et al.*, 2011). The model is based on statistical information without the need for flow measurement. Statistical information on users and end uses is a prerequisite to build the model, where this includes information on occupancy, flow and duration per water-use event, frequency of use, occurrence over the day for all appliances and different end uses such as toilet flushing, hand washing and laundry. The key feature within this model is that it is not based on flow rate measurements and it does not require any information on daily flow rate, as the input variables are statistical data about users and appliances. In spite of the fact that the model was originally developed to estimate maximum water demand in order to design self-cleaning networks, it has been used for many more applications, some of which provide insights into different aspects related to water quantity and quality, and it is now used as a new approach in the Netherlands to estimate water demand in both residential and non-residential buildings.

This approach focused on understanding and determining the peak demand flow which is a crucial parameter for the design of potable water distribution systems inside and outside buildings. The input parameters contain the water use per flush for different types of toilet, the average and variance of shower duration, the flow rate of taps and mixers, the occupant composition and a statistical description of the sleep-wake rhythm of each user for residential buildings. Meanwhile, for non-residential buildings, the model follows a modular format in which each type of building comprises functional rooms. These rooms are categorised by their sanitary appliances and particular groups of users such as employees and visitors. The concept of functional rooms was hence used to develop water demand models for different types of non-residential buildings.

The functional rooms for office buildings, hotels and nursing homes, as shown in Figure 3-4, include a meeting area, restaurant, lodging, fitness room and other technical rooms. The meeting area includes toilets and coffee machines, with the employees and visitors both defined as users. A lodging is a room in a hotel or nursing home that includes a bathroom. These functional rooms include a water closet, water tap, shower or bath, and users engage in water-related behaviour that is more or less residential. In a hotel, the water use of the lodging is defined by the number of guests, while in a nursing home it is instead defined mainly by the number of carers. A restaurant in a nursing home, office building or hotel, is defined by the inclusion of dishwashers and kitchen taps, with kitchen personnel as users. A fitness area in an office or hotel that includes showers is similar to the meeting room in terms of users, but with a lower usage when compared to domestic showers. Other groups contain washing machines and cleaning sinks which are used by people as a part of their day-to-day duties (Blokker *et al.*, 2011)

This approach can be defined as one of the more successful methods in water demand estimation and was adopted in a revised version of the Dutch guidance that was released in 2013. It is regarded as successful because the new equations resulted in a design flow rate very close to the measured flow rate, with a significant reduction when compared with previous guidelines.

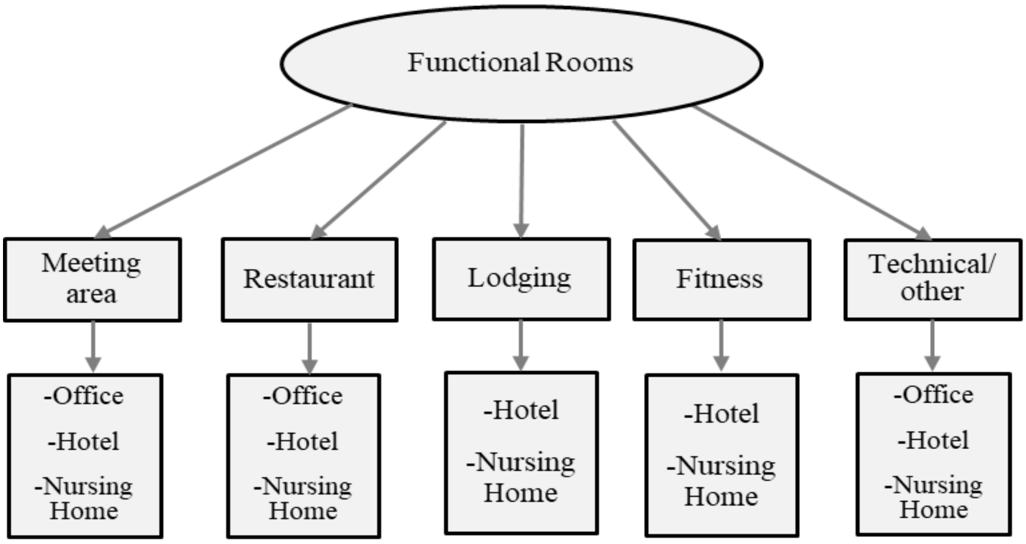


Figure 3-4 Types of functional room for office, hotel and nursing home (Blokker *et al.*, 2011)

The main limitation of this method is that it is relatively complex and needs a specific coding skills to set up the model. The details of the model are not published and the procedures of calculations are not available. Despite the fact that the model established a reliable basis on which to estimate cold and hot water demand for both residential and non-residential buildings, the successful outcome would not have been possible without the statistical information which had been gathered before developing the model. The key challenge, therefore, with using the same approach in the UK is the lack of necessary data as the SIMDEUM model relies heavily on statistical data representative of both sanitary appliances and users. In the Netherlands, before developing the SIMDEUM model, data had been collected in different surveys that involved 3227 individuals in 1995, 1813 in 2000 and 2200 in 2005. Another drawback of this method is that these results were based upon data from the Netherlands and it is unclear if the model is applicable for other countries. Nonetheless, using the Monte Carlo technique in the simulation and the involvement of users as the dominant parameter in calculating design flow for office buildings can be considered as highly advantageous for developing the new model in this study.

3.4.3 Water demand calculator (WDC)

In the USA, a probabilistic approach to determine peak water demand in buildings has historically been used. This is based on the Hunter Fixture Unit method as published in the Methods of Estimating Loads on Plumbing Systems BMS65 in 1940. However, as early as 1974, a US Commission launched a program to develop an enhanced computational method for the design and evaluation of water demand after proving that the application of Hunter's approach results in an overestimation for most types of building. This overestimation was exacerbated by the requirement of the Energy Policy Act of 1992 (EPACT) for appliance flow reductions along with other water conservation measures through the Water Sense program introduced by the U.S. Environmental Protection Agency (EPA). More recently, in response to the reduction in water demand, the American Society of Plumbing Engineers (ASPE) and the International Association of Plumbing and Mechanical Officials (IAPMO) started the task of developing a new model for estimating peak water demands in buildings. Buchberger *et al.* (2017) described the methodology of developing the Water Demand Calculator (WDC) which evolved from the application of different methods of estimating peak demands in buildings including the Wistort Method, the Modified Wistort Method, the Exhaustive Enumeration and the q1+q3 Method. Herein, these methods are briefly described, but for more information interested readers are referred to Buchberger and Omaghomi's works.

a. Wistort's Method

Using the normal approximation for the binomial distribution to calculate peak water demand was proposed by Robert Wistort in 1994. Similar to Hunter's method, the number of busy appliances (k) is considered to be a random variable with a binominal distribution having a mean and variance of E[k] = np and Var [x]= np – (1-p), respectively. In this method, the 99th percentile of the flow rate $Q''_{0.99}$ in the building is defined as:

$$Q''_{0.99} = \sum_{g=1}^{g} q_g \, n_g \, p_g + (z_{0.99}) \sqrt{\sum_{g=1}^{g} q_g^2 \, n_g \, (p_g - p_g^2)} \tag{3.1}$$

where:

- n_g ….. is the total number of appliances of type g
- p_g ….. is the probability that a single appliance of type g is in use (operating)
- q_g ….. is the flow rate at the busy appliance type g
- $z_{0.99}$ …. is the 99th percentile of the standard normal distribution

The best result of application of the normal approximation used in Wistort's approach can be achieved when the dimensionless term $H(n, p)$ in Equation 3-2 ≥ 5. This term is called the *Hunter Number* and represents the expected number of simultaneous busy appliances in the building during peak hours. The total number of appliances must be relatively large to satisfy this condition. Therefore, Wistort's approach is appropriate for estimating demand flow for relatively large buildings, while it is not suitable for small or single family homes.

$$H(n, p) = \sum_{g=1}^{g} n_g \, p_g \tag{3.2}$$

b. Modified Wistort's Method (MWM)

As single family homes do not have large numbers of occupants and appliances, idle appliances can be considered the norm for much of the time including during peak hours. In buildings with separate appliance groups (*g)* the probability that all appliances are off (*P₀*) is:

$$P_0 = \prod_{g=1}^{g} = \quad (1 - p_g)^{n_g} \approx \exp\,[-H(n, p)] \tag{3.3}$$

In the case of using the traditional binomial distribution for a single family home, the high probability of no appliance in use leads to a significant reduction in the average number of busy appliances, resulting in a considerable bias in calculated peak demand. However, designing for zero flow should be avoided so as to prevent inaccurate sizing of the water system. To avoid this and to define a suitable probability distribution for busy appliances, a "*Zero-Truncated Binomial Distribution"* (ZTBD) was introduced by Buchberger *et al.* (2017). Here, it is assumed that it is possible to apply a normal approximation to define the upper tail of the ZTBD. The representation for the 99th percentile of flow rate $Q''_{0.99}$ with g types of appliance is:

$$Q''_{0.99} = \frac{1}{1 - P_0}\left[\sum_{g=1}^{g} q_g\, n_g\, p_g + \{(1 + P_0) z_{0.99}\} \sqrt{\left[(1 - P_0) \sum_{g=1}^{g} n_g\, p_g\,(1 - p_g)\, p_g^2\right] - P_0 \left\{\sum_{g=1}^{g} n_g\, p_g q_g\right\}^2}\right] \quad (3.4)$$

When $H(n,p) > 5$, $P_0 \rightarrow 0$ and Equation (3.4) reduces to Equation (3.1) and the ZTBD method is referred to as the Modified Wistort's Method (MWM). The results of the simulation of indoor water use indicate that the MWM has good performance when $H(n,p)$ 'Hunter Number' ≥ 1.25. The advantage of this method is that when n=1 and g=1 (final appliance on the water supply line) Equation 3-4 simplifies to $Q''_{0.99} = q$, i.e. the design flow is simply the nominal demand of the last appliance.

c. Exhaustive Enumeration Method (EEM)

This approach can be defined as the most straightforward of the computational modelling techniques. Most design approaches, including those from Hunter and Wistort, have focussed on the 99th percentile of water demand as being representative of the design flow rate. The concept of the EEM method is to calculate and evaluate all possible combinations of appliance use and numerically generate the entire probability distribution of water demand at any time and at any point in a building. According to this approach, flow rates and probabilities for every outcome can be calculated to generate an empirical Cumulative Distribution Function (CDF). However, although the EEM may be straightforward when the number of appliances is small, it becomes complex when the number of appliances increases. With increasing appliance number, the size of the problem grows geometrically because of combinatorial growth. For example, with four independent appliances there are 2^4 = 16 possible demand outcomes, while with 12 independent appliances, which is the case in the typical single-family home, there are 2^{12} = 4,096 demand outcomes. Therefore, using this method needs application of other techniques such as Monte Carlo.

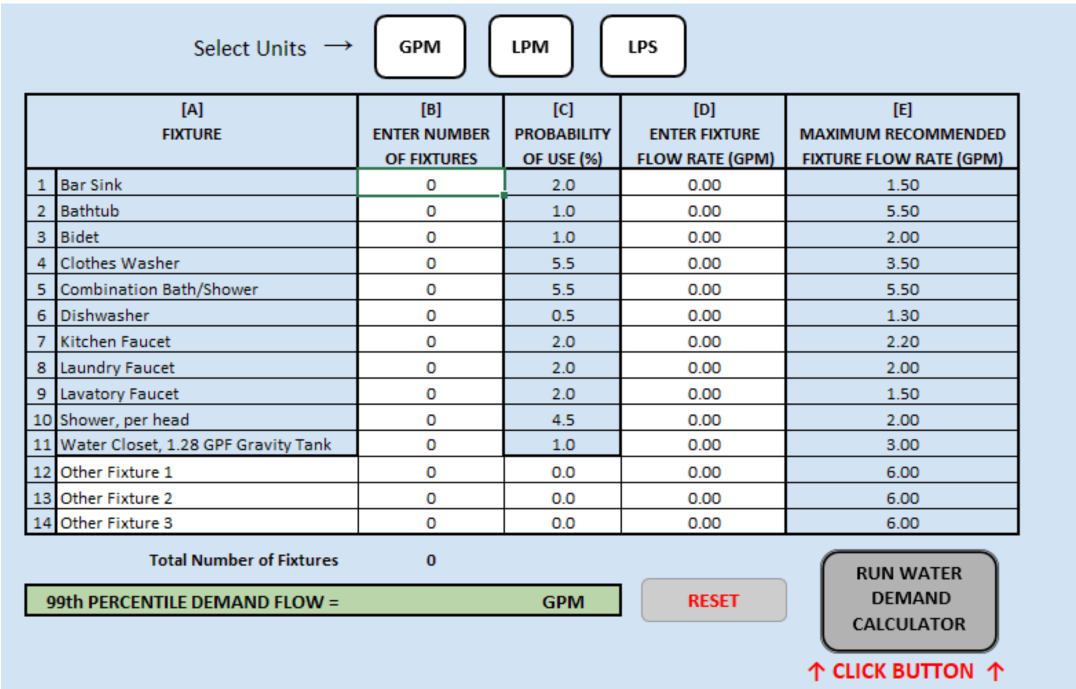
d. $q1 + q3$ Method

During development of the EEM, the tendency of certain combinations of appliances to strike near the 99th percentile design flow led to development of the "$q1 + q3$" method. This can be defined as a special case of the EEN in which the 99th percentile of demand flow occurs consistently with the highest and third highest appliance demand flow. For example, the appliance with the greatest flow rate is allocated a ranking of '1', and the appliance with the second largest flow rate '2' and so on. In the *q1+q3* approach, the demand for the first ranked appliance is added to the demand for that ranked third so as to make an appropriate estimation of the 99th percentile flow rate.

However, the application of the above four methods to estimate demand flow can be challenging since the solution varies with the spatial scale of the water supply system, i.e. peak water demand depends on the type and number of sanitary appliances in the building. For instance, in a large scale building, when the total number of appliances (*N*) is greater than 200, individual appliances may not considerably impact the performance of the plumbing system. Consequently, approaches like the Wistort Method can be applied to estimate demand flow using well established continuous probability distributions, whilst, in small scale buildings when the number of appliances (*N*) is smaller than 20, individual appliances exert a considerable effect on system behaviour. In this case, methods like EEM or $q1 + q3$ are required because they consider discrete appliances in premise plumbing. Thus, the approach best suited to calculate peak demand flow might change as the appliance count or building scale increases. The WDC was developed as a design tool to tackle this challenge and help in the selection of an applicable method to calculate peak demand flow in buildings.

The WDC can be defined as an improved approach to estimate demand flow for single and multi-family dwellings. The main advantage of the WDC is its ability to avoid overestimation of demand flow resulting from Hunter's method. One further advantage of this new WDC method is that in addition to its accuracy in estimation of water demand, it is very easy to use, enabled by a downloadable Excel spreadsheet, Figure 3-5. However, the main limitation of this approach is that it is constrained to residential buildings only and it fails to consider other types of buildings, i.e. non-residential buildings. The approach does not take into account users and the results depend wholly on the properties of the sanitary appliances. The accuracy of the approach, therefore, is dependent upon the data on appliances and upon the probability distribution used. The WDC is, moreover, the result of long-term work dating back to the 1990s, and the extensive water demand data required for the model was collected from more than 1000 households surveyed between 1996 and 2011. In addition, commercial products were used to disaggregate the flow rate data to represent individual water use events. Unfortunately, such an extensive and high resolution data set is not available in the UK. Since no detail is given on procedure and calculation, the performance of the model in other countries might also be questionable.

Approaches of this kind carry with them various well known concepts and successful outcomes. Hence, the same essential parameters of appliance characteristics, the correct probability distributions and Monte Carlo technique are recommended for this study.



Select Units → GPM LPM LPS

	[A] FIXTURE	[B] ENTER NUMBER OF FIXTURES	[C] PROBABILITY OF USE (%)	[D] ENTER FIXTURE FLOW RATE (GPM)	[E] MAXIMUM RECOMMENDED FIXTURE FLOW RATE (GPM)
1	Bar Sink	0	2.0	0.00	1.50
2	Bathtub	0	1.0	0.00	5.50
3	Bidet	0	1.0	0.00	2.00
4	Clothes Washer	0	5.5	0.00	3.50
5	Combination Bath/Shower	0	5.5	0.00	5.50
6	Dishwasher	0	0.5	0.00	1.30
7	Kitchen Faucet	0	2.0	0.00	2.20
8	Laundry Faucet	0	2.0	0.00	2.00
9	Lavatory Faucet	0	2.0	0.00	1.50
10	Shower, per head	0	4.5	0.00	2.00
11	Water Closet, 1.28 GPF Gravity Tank	0	1.0	0.00	3.00
12	Other Fixture 1	0	0.0	0.00	6.00
13	Other Fixture 2	0	0.0	0.00	6.00
14	Other Fixture 3	0	0.0	0.00	6.00

Total Number of Fixtures 0

99th PERCENTILE DEMAND FLOW = GPM

RESET

RUN WATER DEMAND CALCULATOR

↑ CLICK BUTTON ↑

Figure 3-5 Screenshot of a template of WDC (*WE Stand*, 2018)

3.5 Selecting an appropriate model and key considerations

It is important, at this point in the research, to assess the different types of models commonly adopted and to review the successful approaches that have been developed. The text above provides the links between statistical models and recent studies undertaken to better estimate design flow rate. After undertaking a critical analysis to reveal the advantages and limitations of each method, the following conclusions are drawn. Firstly, in general, the traditional probability models, as they are currently deployed, result in notable overestimation of demand flow rate. Even making changes in the allocation of LUs and providing new LUs for additional appliances have not improved water demand estimation to an acceptable level. Updates to British Standards and the provision of different versions have demonstrated that the probability model alone is unlikely to enable an accurate estimate of design flow. Secondly, empirical approaches need large data sets to develop a robust model to cover all types and scales of building. The success of the empirical model mainly depends on the quality and quantity of the data, whether secondary or primary. There are very few data sets, if any, that provide flow data for non-residential buildings. In addition, empirical models cannot be adapted to changes that occur in the future, for example, in users' behaviour and appliance efficiency. Thirdly, despite its complexity, the stochastic model is seen to underpin most successful outcomes from recent approaches. Using the Monte Carlo technique and appropriate probability distribution has confirmed the effectiveness of this type of model in water demand estimation. Furthermore, this approach does not reply upon flow rate data; a positive aspect for this study in terms of time and cost saving on one side, and adaptability of the model for future change in water use habits on the other side. The decision was hence made to proceed with development of a stochastic model.

The most recent and successful approaches in water demand modelling have emphasised the need to use techniques such as Monte Carlo to capture all simultaneous uses of sanitary appliances. This is because the Monte Carlo technique enables probability distributions that capture all possible outcomes for simultaneous water use. In addition, there is a clear attempt to involve users in a direct or indirect way in water demand modelling. Therefore, users could be a key factor, if not the only one, in estimation of demand flow rate in buildings.

Thus, the information necessary to develop a robust stochastic model was classified into two categories: i) input parameters to develop the model, including information about the buildings, users and sanitary appliances (type and number of appliances, flow rate and *p*-value) and ii) flow rate measurement to validate the model. Flow rate data can also be used to understand water usage patterns and to make comparisons between actual, design and simulated flow. For this purpose and as preparation to develop a new stochastic model, relevant definitions and associated requirements are provided in the following sections.

3.6 Selecting a specific type of non-residential building

Water demand patterns differ depending on the type of buildings under consideration. As a reminder, this research focuses specifically on non-residential buildings. In general, buildings can be classified into two main groups depending on their functionality: residential and non-residential buildings. There has been very little research on estimating water demand in non-residential buildings. This is because most of the design guides focus on residential buildings and leave much to the judgement of designers for non-residential buildings.

Buildings are usually categorised according to the purposes for which they are being used. The use of buildings is one of the essential factors that should be considered during applying for planning permission or prior approval for any building. In the UK, the use of land and buildings is divided into different categories according to UK Statutory Instruments (1987, 2020). The version 2020 (Use Classes) amended the 1987 version and introduce some changes to the system of Use Classes. Table 3-2 provides a brief summary of building classification and the amendments, while more details are available in the Town and Country Planning Orders (1987 and 2020).

Table 3-2 Building classification according to the UK Statutory Instruments (2020)

Class	The Town and Country Planning (Use classes) 1987	The Town and Country Planning (Use classes) 2020
	Part A	
A1	Shops	
A2	Financial and Professional services	
A3	Food and drink	
	Part B	
B1	Business	
B2	General industrial	
B3	Special Industrial Group A	
B4	Special Industrial Group B	
B5	Special Industrial Group C	
B6	Special Industrial Group D	
B7	Special Industrial Group E	
B8	Storage or distribution	
	Part C	
C1	Residential institutions	
C2	Dwelling houses	
	Part D	
D1	Non-residential institutions	
D2	Assembly and leisure	
		Part E
E		Commercial, Business and Service
		Part F
F1		Learning and non-residential institutions
F2		Local community
		Sui Generis

In terms of design of the water system and sanitary facilities in buildings, the building classification may be less complex as it mainly depends on user behaviour in using water and on functionality of the building. Depending on the type of building, the British Standard BS 6465 gives detailed guidance on the design of sanitary facilities and provides a recommended scale of provision of sanitary appliances. This standard provides general recommendations for all sanitary facilities, including layout, walls, floors, ceilings, lighting, heating, ventilation, electrical wiring and fittings, access, and location. According to BS 6465, buildings are categorised into 12 types as follows:

1. Private dwellings
2. Residential and nursing homes for older people
3. Workplaces
4. Shops and shopping malls
5. Petrol stations
6. Schools
7. Assembly buildings where WCs are used during concentrated times (such as theatres, cinemas, concert halls, and similar buildings)
8. Assembly buildings where WCs are not used during concentrated times (such as exhibition centres, libraries, museums and similar buildings)
9. Bedrooms in hotels, hostels, and similar accommodation
10. Restaurants and other areas where seating is provided for eating and drinking
11. Licensed pubs, bars, nightclubs and discotheques
12. Swimming pools

Thus, non-residential buildings include a wide range of building types depending on their usage. In turn, non-residential buildings can be divided into sub-groups such as workplaces, offices, hospitals, schools, shopping centres, hotels, nursing homes, etc. While the users' primary role in determining water demand and diurnal water usage patterns remains a specific feature of all types of non-residential buildings, the nature of using water, maximum flow rate and peak hours may also differ across sub-groups.

The WDEM can be applied to any non-residential building which has diurnal water usage patterns, but the accuracy still needs to be checked by comparing the result with actual flow rate data. To derive new design equations, the workplace was selected as the building type for application of the WDEM. As well as the wide range of sizes and scales of workplace, the availability of suitable case study buildings for gathering data on users, appliances and flow rate was an additional motive for selecting this type of building. However, a wide range of non-residential buildings can be classified as workplaces depending on the building's functionality. In relation to the UK, BS 6465-1:2006+A1 (2009) defines a workplace as any non-domestic premises made available to any person as a place of work and includes any place within the premises to which such a person has access while at work. Based on this definition, other non-residential buildings, such as hotels, schools, nursing homes, shopping malls, petrol stations, restaurants, pubs, bars, nightclubs are not included.

Despite the fact that the term ‘workplace’ covers a wide range of buildings including offices and mixed-use buildings, the application of WDEM was limited to workplace buildings with the following features:

i) Workplaces that operated during normal working hours of around 9:00 to 18:00. Working hours may be different depending on the building’s functionality, while the maximum capacity of the building remains the same. This means that if the building needs to be used by other people, additional shifts need to be considered. In this case, maximum capacity of the building usage itself should be used to estimate demand flow, while the building may have different peak hours. The accuracy of the model, therefore, will need to be checked if the building is used at hours other than normal working hours; for example, in buildings that are used in two or three shifts, i.e. 18 or 24 hours.

ii) As oversizing of the water supply system can be seen in relatively medium and large scale buildings, the model can be applied to workplaces that contain a canteen, coffee shop, and other shops as a part of the building. All parts of the building together can be considered as one building (workplace) to calculate the provision of sanitary appliances and estimate demand flow rate if all receive water from the same main pipe in the network, i.e. when there is no separate pipe distribution for a part of the building.

3.7 Considering users in water demand modelling

Users can be defined as a key element in water demand modelling for all types of buildings. It is important to consider users as a dominant variable in the new model as this is the main factor affecting water demand. In residential buildings, groups of users can be categorised based on their age, size, gender and occupation. The number of people per household is of importance because the frequency of use is typically calculated per person. Previous studies have demonstrated various relationships between age and frequency, between age and shower duration and between water usage rate and household size. Moreover, the time of water use is strongly related to the user’s daily habits such as presence at home and sleep-wake rhythms. Therefore, in residential buildings, the major household types are divided into one-person, two-person, and family (with children) household.

For non-residential buildings, users are typically defined as a group rather than as individuals. The properties of a user group include diurnal pattern and the ratio of males to females. Distinction of gender is important in non-residential buildings as it may affect toilet use, in particular when the washrooms have urinals and toilets. In a specific type of non-residential building such as workplaces, the most important information on users includes the number of employees, the number of visitors, and overall working time. The dominant variable in workplaces can therefore be defined as the users that contribute most to the pattern and total amount of water use in the building. Additionally, number of users can also be used to identify the number and type of sanitary appliances in any building during the early stages of the design process. Therefore, recording the total number of people is important in this study as it is considered to be the main driver of water use. In a small building with only one entrance, it may be possible to count the number of people in the building manually, while in relatively large buildings, manual counting may not be possible and a different method should be undertaken. With today's technology, new techniques can be used for this purpose. In this study, both approaches were used to count the number of people in the case study buildings.

3.8 Types of appliances and their flow rates (discharge) *q*

Sanitary appliances are the points in buildings where water is discharged and have a direct effect on water demand. In general, there are nine main types of sanitary appliance: WC, urinal, hand wash tap, shower, kitchen tap, washing machine, dishwasher, bathtub, and outside tap. However, for a non-residential water-demand model, these types may be extended to include a cleaner's sink and reduced to exclude appliances such as the bath and washing machine which rarely exist in this type of building. Outdoor water use has also been neglected because of its limited contribution in non-residential buildings. Additionally, drinking water and coffee machine points have not been considered because these points are usually fed from the mains supply in most of the buildings where storage tanks are used. Thus, depending on the building usage, sanitary appliances in workplace buildings may include WC, hand washing taps, urinal, shower, kitchen sink, cleaning sink, and dishwasher. Each kind of end use is divided into different sub-types. For example, a WC may be an older type with a large cistern of 9-12 litres or a new double-flush consuming either 6 litres or only 3 litres with a water-saving option. The shower sub-type is determined by the intensity of the flow. The washing machine and dishwasher sub-types are determined by brand and water inlet pattern. For example, a front-load washing machine has a different inflow pattern and significantly lower total water use than a top-load washing machine. The kitchen tap sub-types are defined by use, such as dishwashing, handwashing, consumption for meals or tea/coffee etc.

In addition to the type of sanitary appliance, their flow rate is another important factor in water demand modelling. The design flow rate for any building strongly depends on the flow rate of appliances. Reductions in flow rate in newer appliances and using a water-efficient model can be considered as one of the main factors in reducing demand flow in buildings. In this study, the flow rate of appliances was obtained from manufacturers' specifications or alternatively from direct measurement as explained in the following sections.

3.8.1 Manufacturers' specification:

Flow rate information is typically provided in the appliance installation guide. In response to water labelling requirements, all manufacturers are required to indicate their products' water consumption to help people select water efficient products. It is now possible to access information on most popular brands of sanitary appliances through the internet. The website "Europeanwaterlabel.eu", for example, summarises all available information on sanitary appliances produced in Europe (including the UK). This site provides details on registered companies and their products' specifications (including flow rate). According to *The European Water Label* (2020), sanitary appliances are classified into five categories based on their flow rates as shown in Figure 3-6. More than 5000 different types of basin tap, kitchen tap, shower and WC are available in the UK. As expected, most products can be classified as water-efficient, especially basin taps and WCs which are used most frequently in non-residential buildings. Figures 3-7 and 3-8 classify the different sanitary appliances available in the UK based on their water consumption. For example, more than 2,600 types of basin taps are available, of which 67% have flow rates between 1.3-6.0 *l/m*. This analysis was used to make decisions about the flow rate of the sanitary appliances in the model proposed herein. The average value of flow rate for each group of appliances (A to E) was applied to the model to simulate design flow rate and derive design equations.

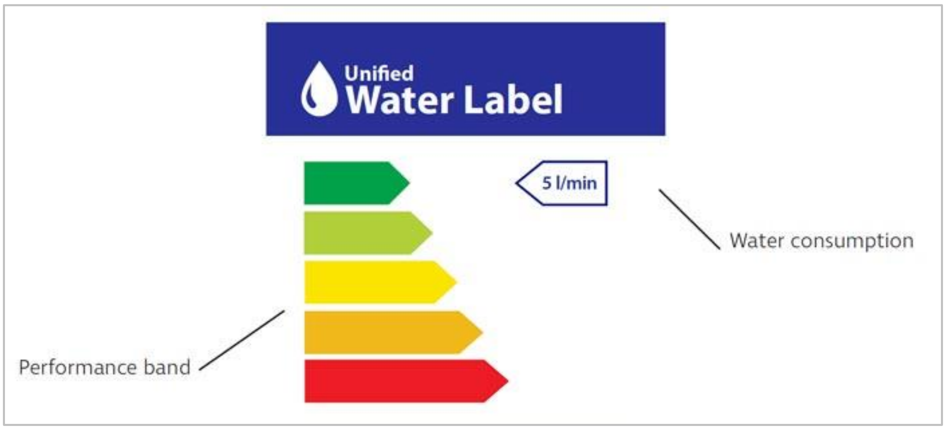


Figure 3-6 European water label

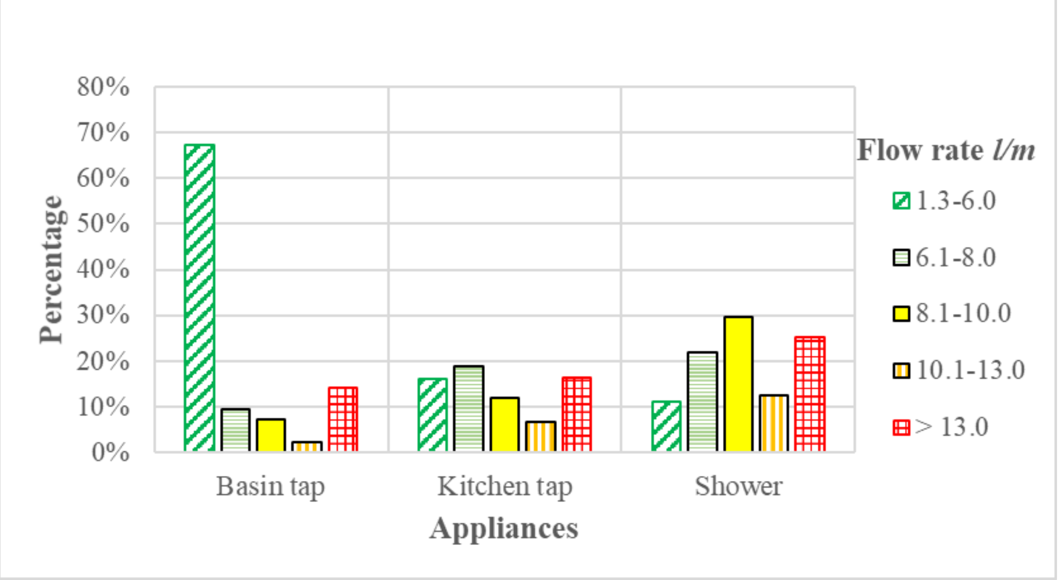


Figure 3-7 Classification by percentage of available basin taps, kitchen taps & showers in the UK based on water consumption

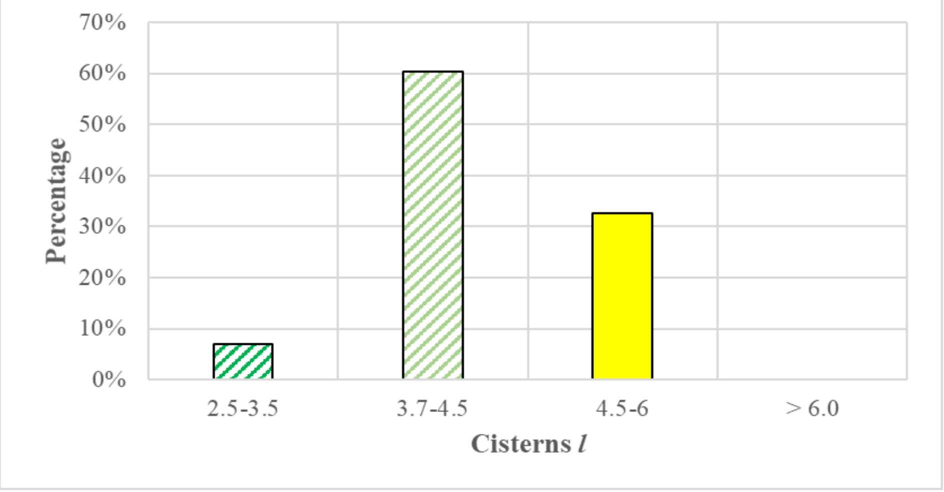


Figure 3-8 Percentages of available WCs & Urinals in the UK based on cistern capacity

3.8.2 Direct flow measurements

When information on the flow rate of appliances is not available, this can instead be measured. For example, water discharge from a tap, mixer tap and shower can be measured by fully opening the tap and measuring the amount of time it takes to fill a container of pre-defined volume. In the same way, flow rates for filling WCs and urinals can be found after determining the capacity of the corresponding cistern.

During direct measurement, the flow rate of appliances of the same type may vary depending on the time (e.g. peak hour) and location (e.g. lower or upper floor). Therefore, the average flow rate, Equation 3-5, was used for a given type of appliance. It is worthy of mention that direct measurement was undertaken in the case study buildings to apply measured flow rate within the model to estimate design flow rate.

$$q_{avg} = \frac{\sum q}{Total\ No\ of\ appliance} \tag{3.5}$$

3.9 *The probability that appliance is in use "p-value"*

The *p*-value is one of the key input parameters for the model and represents the probability that an appliance is in use, i.e. the probability that water is flowing. It is defined by two time intervals: duration of using the appliance and time between successive uses, Figure 3-9, and presents as a dimensionless ratio, Equation 3-6:

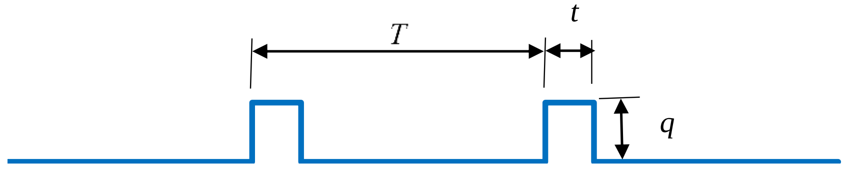


Figure 3-9 Two key time intervals (*t* & *T*) when a single appliance is in use

$$\boldsymbol{p} = \frac{\text{Average duration of time that the appliance is in use } (\boldsymbol{t})}{\text{Average time betweeen successive uses } (\boldsymbol{T})} \tag{3.6}$$

Practically, T can be difficult to determine; therefore, Buchberger, Omaghomi, Wolfe, Hewit, & Cole (2015) replaced this with an observation time which focussed on the peak hour of water use (60 minutes). Thus, the *p*-value can be calculated using Equation 3-7.

$$p_h = \frac{\sum_1^n t_{(i,n)}}{T} \tag{3.7}$$

where:

p_h is probability that the appliance is busy in peak hour

t is the duration of time that the appliance is in use in minutes

n is number of appliances of the same type

i is number of usages

T is the time between successive uses:

$$T = nD \tag{3.8}$$

D is peak hour observation period in minutes

Establishing the *p*-value requires flow rate monitoring at the individual water appliance, i.e. toilet, washbasin, etc. There are different methods for determining *p*-value. Larson *et al.* (2012) presented in detail the methods of determining *p*-values, and a brief discussion of these methods is provided in the following sections.

3.9.1 Pressure-based sensor

One of the methods that can be used to determine the frequency of use of sanitary appliances is that of monitoring water pressure in the plumbing system. This method depends on measurements taken in a dwelling and utilises readings recorded by a pressure transducer located at a single point in the water supply pipeline. Opening or closing any sanitary appliance produces unique pressure transients that can be disaggregated and mapped to individual water usage. This technique can also be used to determine the volume of water being used at each appliance depending on the change in the pressure. Figure 3-10 shows an example of typical pressure sensor traces. Each stream correlates with a water use event when a valve is opened, sustained for a period of time, and then closed. In this figure, filtered pressure (black), raw pressure (shaded lines), and appliance operations (the highlighted areas) are all shown (Larson *et al.*, 2012). In this method, each water use event is disaggregated from the data-stream by identifying the start and end points, after which it is then categorised as a valve 'open' or valve 'closed' event. Figure 3-11 shows identification of event segmentation and overlapping events for a shower, toilet and faucet valve (Larson *et al.*, 2012)

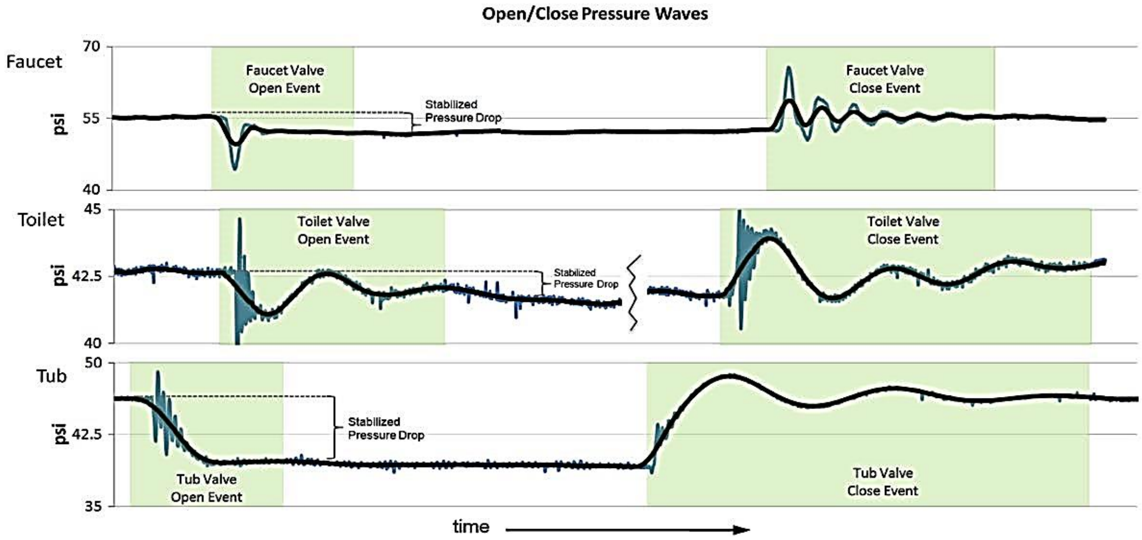


Figure 3-10 Examples of pressure transients for different types of appliances

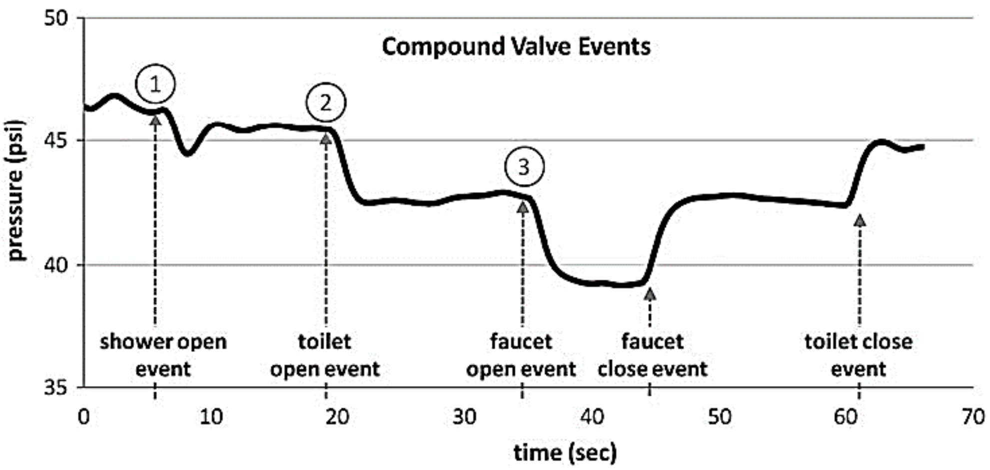


Figure 3-11 Event segmentation for overlapping different appliances

Initial results show the effectiveness of the approach and provide a basis for future analyses and improvements. In addition, this method can automatically provide results without the need for post-data collection analysis and classification. The technique is also able to differentiate between two of the same appliances in the same house with an acceptable level of reliability.

Although this method shows significant promise as a practical, low cost, unobtrusive approach to obtain the specific flow and volumes of water used by individual appliances, initial results and testing indicated poor performance in homes which do have not separate metering, due to water events from one home being detected in a neighbouring home. Another limitation with this approach is that it does not explain how accurate the method is in situations where the pressure in the water system is not stable or where there are a large number of appliances (as is usually the case in non-residential buildings). In addition, its usage was limited to a specific project carried out in the USA and currently it is not available for public use; therefore, it cannot be used in other studies or in other countries.

3.9.2 Flow Trace analysis

This method depends on flow rate data obtained from a water meter or flow meter installed on any given main supply pipe. Data are typically analysed using proprietary software where it is possible to convert this to individual flow rates for appliances based on the amount of water used and on operation duration, as shown in Figure 3-12. This approach has been used in studies undertaken in the USA for such purposes as identifying leakages in household plumbing systems (Larson *et al.,* 2012).

The key challenge with this approach is that it cannot make any distinction between appliances of the same type. For instance, depending on flow rate, it can recognise that a tap is responsible for a water use event, but where more than one tap exists (even different tap types such as toilet or sink) it cannot identify which one was responsible for the water event.

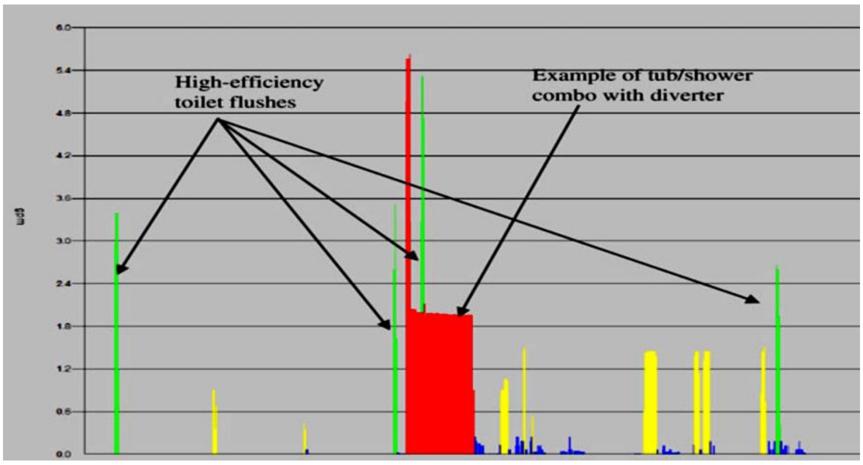


Figure 3-12 Example of flow trace analysis output

3.9.3 Computer software

Flow rate data can be analysed using numerical software which often includes a decision tree concept to classify total flow arising from individual appliance usage events. This method requires high quality flow data and information on sanitary appliances, including types of appliances, their flow rate (average and maximum) and duration of use. The decision tree concept is illustrated in Figure 3-13. This model was built by the Water Resources Consulting group (WRc) in the UK and was used to investigate micro-components' water usage in three case study buildings (Larson *et al.*, 2012).

Although this method can be described as cost-effective, sufficiently accurate and straightforward to apply, this bespoke technique falls under the ownership of WRc and is not available for purchase or rent. It is also unclear precisely how well the approach would perform when applied to different types of building. The application of this method is suitable for relatively small buildings, while the process of disaggregation of water usage events may be challenging with increasing number of users and appliances.

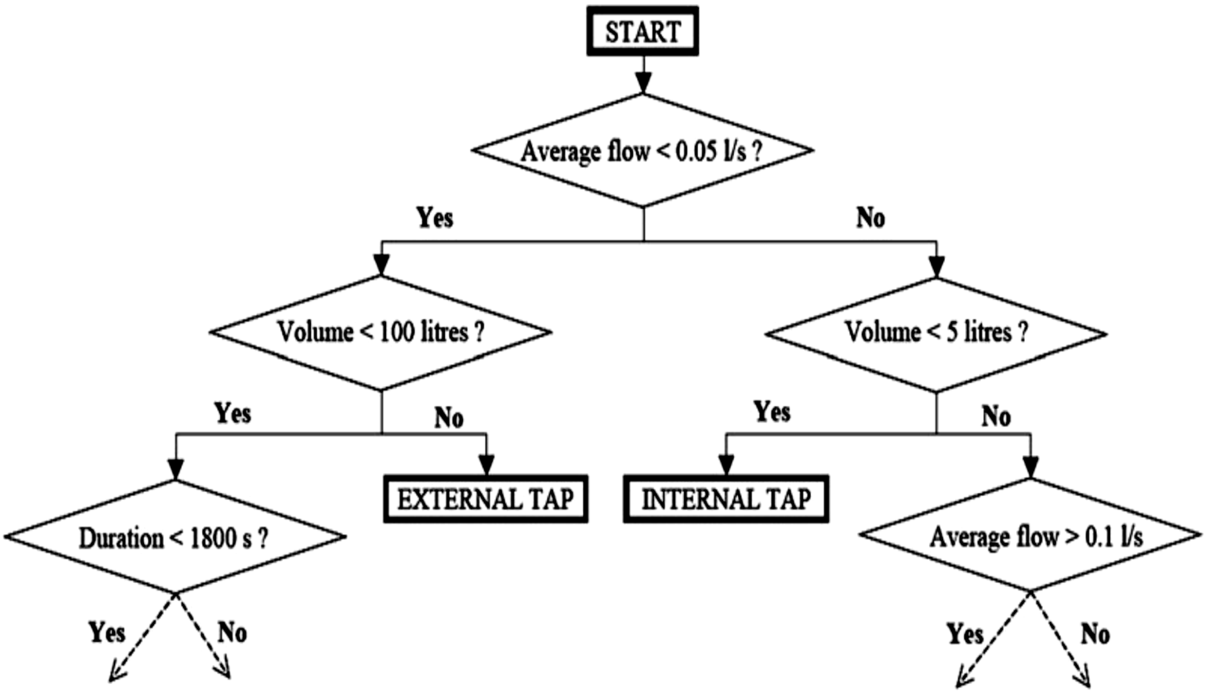


Figure 3-13 Simple decision tree example

3.9.4 SIMDEUM

This water demand estimation model depends on information on user behaviour and on sanitary appliances that has been gathered from: i) surveys that outline the frequency and duration of use of appliances, and for residents, sleep/wake and work/rest patterns etc.; ii) national statistics to establish household number, age, occupancy, etc.; and iii) manufacturing manuals to record technical specifications of sanitary appliances (Blokker, 2010).

To disaggregate total water demand, the model creates individual rectangular pulses for water usage events; each has a start time, duration and intensity. The output of the model is values of flow rate for each appliance and its duration time. Figure 3-14 presents an example of the model's input and output. This approach can be defined as a low-cost and time-saving method when compared to some other water demand measuring approaches (Blokker, 2010; Larson *et al.*, 2012)

The main limitations of this method are that it is relatively complex to set up and relies on an extensive data set which was collected in the Netherlands. Gathering this amount of data can be challenging; and it is not clear if this method would be suitable for non-residential buildings where the number of appliances is generally much higher. Additionally, this approach does not consider the impacts of fluctuations in system water pressure.

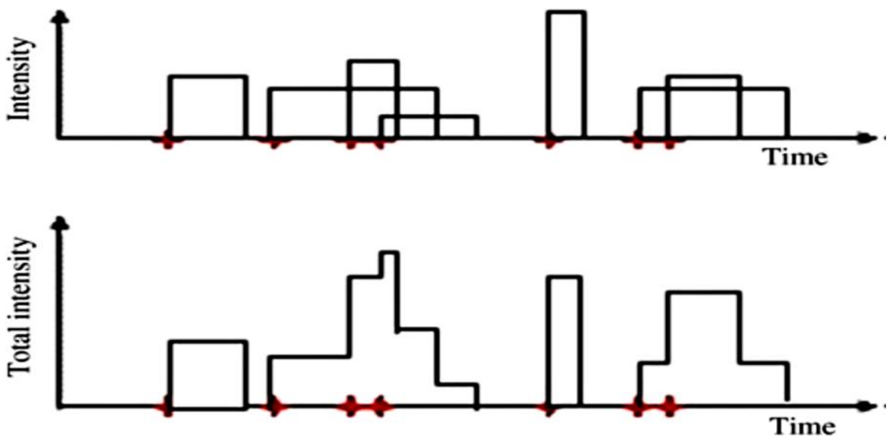


Figure 3-14 Example of SIMDEUM output (Blokker et al. 2008)

3.9.5 Diary survey

This method depends on qualitative data on water usage patterns in buildings and requires participation of a large number of individuals, selected in a way that is representative of the overall sample. Typical mechanisms for data collection include: i) questionnaire: referring to, for example, building, appliance and occupant characteristics, ii) diary survey: recording the frequency and duration of water usage activities iii) testing of sanitary appliances to record flow rate, volumetric consumption and duration of use. All observed data should then be processed, normalised and represented statistically to predict water use events (Larson *et al.*, 2012). The diary survey approach is usually low cost because there is no need for the installation and calibration of specific equipment. It is also reasonably reliable in its recording of human behaviour (Morrison and Friedler, 2015).

Although the method can be readily employed for different types of buildings, such surveys are only practical over a short timescale and for a specific place. However, such short-term surveys do not necessarily demonstrate detailed changes of water usage over time and they provide only a snapshot of user behaviour. Additionally, because of their dependence on the willingness of participants, it can be difficult to obtain a sufficiently large sample to fully address all relevant factors. Also, those people who agree to participate in such studies may modify their water usage patterns when they are aware of the observation. Consequently, results may need to be compared with measured flow rate data to check accuracy.

3.9.6 Direct metering

Direct metering involves installing flow meters at each water-using micro-component, usually alongside an additional meter at the main entry pipe to be used as a reference and check on the total flow (Larson *et al.*, 2012). A good example of direct metering is offered by the study carried out by Edwards and Martin (1995) in which the water consumption of 2000 homes in the UK was investigated across a one-year period. Here, a flowmeter was installed inside each of 100 homes at every individual appliance. On average, 14 meters per household were installed in positions considered least obtrusive. Flow rate data were recorded remotely and downloaded through the telephone network service. The total flow rate of the individual flow meters was regularly compared with the reference meter for quality control. The advantage of this method is that it has the ability to capture actual flow rate for each appliance separately.

However, the problem with this method is the difficulty in installing several flow meters in each household. This difficulty is compounded when it is necessary to install meters in non-residential buildings with a large number of appliances. The high overall cost is perhaps another significant disadvantage. In addition, finding participants who are willing to allow the installation of a large number of meters in their home might also be challenging.

3.9.7 The CIPHE and other scientific studies

Given that *p*-value is an important input variable in most water demand estimation approaches, scientific studies and surveys have been undertaken to determine *p*-values of sanitary appliances. One design guides that provides a comprehensive list of *p*-values is that of the CIPHE (Chartered Institute of Plumbing and Heating Engineering). The key strength of this guide is that the *p*-values were calculated based on information obtained from the UK. This guide provides both *t* (the duration of time that the appliance is in use) and *T* (the average time between successive uses) to calculate *p*-values for each appliance. Importantly, the same value of *t* has been used alongside different values of *T* to calculate *p* for different types of building based on frequency of use for both residential and non-residential buildings. Figures are predicated on a 1200 second gap between each event for low use buildings such as dwellings and other buildings where appliances are used by a single person or a small group. For medium use, this gap is 600 seconds; applicable to buildings that are used by larger groups of people and in which a random basis with set time constraints is not required, such as public toilets. High use is considered to correspond to a 300 second interval, which would be the case within buildings where the appliances are used by a large group of people over a short period, such as in theatres. Table 3- 3 shows the values of *t*, *T* and *p* for different types of appliances.

In addition, Omaghomi and Buchberger (2014) and Buchberger *et al.* (2017) considered the *p*-value as one of the main input parameters in developing the Water Demand Calculator (WDC). They used indoor water use measurements collected by a commercial company from over 1000 single-family homes across the USA to determine *p*-values, and the recommended design flow rates and *p*-values are summarised in Table 3-4. However, while *p*-values from this study were successfully applied in the WDC with good outcomes, it may not be possible to use them in this study based on two important limitations: first, the data was collected from residential buildings; second, water use habits in the USA may be different from the UK.

Table 3-3 The values of *t, T* and *p* in CIPHE guide

Type of appliance	***t*** ***second***	***T*** ***second***	***p***
Basin, 15mm sep. taps	33	1200	0.028
	33	600	0.055
	33	300	0.110
Basin, 2 x 8mm mix. tap	33	1200	0.028
	33	600	0.055
	33	300	0.110
Sink, 15mm sep/mix tap	60	1200	0.050
	60	600	0.100
	60	300	0.200
Sink, 20mm sep/mix tap	60	600	0.100
Bath,l5mm sep/mix/tap	266	4800	0.055
	266	2400	0.111
	266	1200	0.222
Bath, 20mm sep/mix tap	266	300	0.089
WC Suite, 6.litre cistern	60	1200	0.050
	60	600	0.100
	60	300	0.200
Shower, 15mm head	300	2700	0.111
	300	1800	0.167
	300	900	0.333
Urinal, single bowl/stall	1500	1500	1.000
Bidet, 15mm mix tap	33	1200	0.028
	33	600	0.055
Hand Spray, 15mm	75	1200	0.067
Bucket sink, 15mm taps	60	3600	0.017
Slop Hopper, cistern only	75	600	0.125
Slop Hopper, cistern/taps	60	600	0.100
Clothes washing m/c, dom	25	600	0.042

Table 3-4 Recommended design flow rate and *p* value

Fixture	Flow rate (GPM) Data and Specifications	Flow Rate from Database (GPM) 95th and 99th percentile	Recommended Design Flow Rate (GPM)	Design P value
Shower	2.0@80psi [1]	2.4, 2.5	2.0	0.025
Toilet 1.28 gpf		3.1, 3.7	4.0	0.010
Kitchen faucet	1.8@60psi 2.2 @60psi (temp over-ride) [2]	1.4,1.6	2.2	0.025
Lavatory faucet	1.5 @60psi [1]	1.4, 1.6	1.5	0.025
Laundry faucet (with aerator)	2.0@60psi [3]	1.4, 1.6	2.0	0.025
Hi Flow Tub filler – whirlpool type	20.0 @60psi [4]		20.0	0.005
Tub Filler – standard standalone bathtub		6.8, 8.4	7.0	0.005
Combination Tub/shower			4.6	0.030
Dishwasher	1.3@35psi [5]	1.5, 1.6	1.6	0.005
Clothes Washer – vertical axis – heavy load	3.0-4.0@35psi [5]	4.0, 4.5	4.5	0.050
Clothes Washer – horizontal axis - heavy load	3.0@35psi [5]	4.0, 4.5	4.5	0.050
Bathroom Group – Lavatory, toilet, combination T/S			7.0	0.065
Kitchen Group – Sink , Dishwasher			3.8	0.030

[1] EPA WaterSense Specification
[2] From the 2012 Green Plumbing and Mechanical Supplement
[3] American Standard specification sheet for Product No. 2475.550
[4] American Standard specification sheet for Model R800 Deck mount tub filler
[5] Courtesy of the Association of Home Appliance Manufacturers

3.10 Establishing number and type of sanitary appliances based on number of users

Deriving design equations to estimate demand flow for a wide range of workplaces requires the application of the model to different sizes of buildings from small to large scale. Establishing the relationship between number of users and provision of sanitary appliances provides a framework for the model in which the appropriate numbers and types of sanitary appliances are set up for different numbers of users. Thus, instead of using a random number and type of appliances to represent different sizes of buildings, organised groups of appliances were set up based on numbers of users as recommended by the UK standards and guides. The user-appliance relationship also helps free the model from existing multi variables in the final design equations, i.e. instead of using variables such as flow rate, probability and frequency of use of appliances, only the number of occupants will be considered as a dependent variable in the design equations. This section, therefore, explains the correlation between number of users and required number and type of appliances in workplaces.

As explained in the previous section, the workplace has been selected as the building type for setting out the number of sanitary appliances and applying the developed model. British Standard BS 6465 provides recommendations for sanitary facilities in different types of buildings and details design requirements including layout, walls, floors, ceilings, lighting, heating, ventilation and the selection of appliances. For non-residential buildings, it provides additional design considerations for sanitary and associated appliances, and notes that fittings and finishings should be robust and vandal resistant. Further recommendations for male, female and accessible toilets, as well as drinking water, cleaners' rooms, bathrooms, kitchens, laundries and utility rooms are given. Importantly, this guide offers recommendations on the provision of sanitary appliances based on the number of persons using the building. For workplaces, BS 6465 provides the minimum scale of provision of sanitary appliances dependent upon number of persons in the building as shown in Tables 3-5 and 3-6.

Table 3-5 Sanitary appliances for both female and male staff where no urinals are installed in workplaces

Number of persons at work x	No. of WCs	No. of Washbasins
1-5	1	1
6-15	2	2
16-30	3	3
31-45	4	4
46-60	5	5
61-75	6	6
76-90	7	7
91-100	8	8
Above 100	8 plus 1WC and WB for every unit or fraction of a unit of 25 persons	

Table 3-6 Sanitary appliances for male staff where urinals are installed in workplaces

Number of persons at work x	No. of WCs	No. of Washbasins	No. of Urinals
1-15	1	1	1
15-30	2	1	2
31-45	2	2	2
46-60	3	2	3
61-75	3	3	3
76-90	4	3	4
91-100	4	4	4
Above 100	4 plus 1WC, WB and urinal for every unit or fraction of a unit of 50 males		

The recommended ratios of sanitary appliances given in the tables above can be used to generate a range of appliance groups for pre-defined numbers of users. Increasing the number of people replicates an increase in the size of the building and thus enables the study to deal with buildings from small to large scale. In developing the new model, it is important to take into account all considerations and assumptions in setting out the provision of appliances. The most, as defined in BS6465 are:

- the gender ratio should be considered in determining the number of persons before using the tables above to calculate the number of appliances. If information about the gender ratio of occupants is not available, as is the case herein, a ratio of 60% of female and 60% male toilets may be provided, i.e. 120% provision where separate facilities are used.

- the population of normal offices may be determined depending on levels of density from 1 person per 10 m^2 to 1 person per 6 m^2. Detailed measurement rules can be found in the Code of Measuring Practice - A guide for property professionals produced by the Royal Institute of Chartered Surveyors.

- staff in workplaces should not have to walk more than 100m or go up or down more than one floor to use the sanitary facilities. Thus, sanitary facilities on each floor should be sufficient for the number of staff working on each floor.

- it is assumed that the building is fully occupied and allowance has already been made in the numbers of appliances shown in the tables for the fact that the buildings are unlikely to be used to full capacity most of the time, and numbers of users are not to be reduced further.

- using the sanitary facilities for calculating the number of persons should reflect normal peak use. Otherwise, numbers of persons used to calculate fire escape provision may be used as a guide.

- shower facilities for cyclists should be considered and one shower per 100 staff or per 10 bicycle space is recommended.

- any accessible toilet can be counted as part of the overall toilet provision for the building.

- at least one cleaners' room (bucket sink) should be provided in all buildings over 100 m^2.

It is important to note that increasing the number of toilets by 20% to account for gender and the assumption of fully occupying the building helps free the model from the constraints of minimum provision of appliances given in the tables above. This means that at this stage of the study, this provision of appliances can be used in the model without using any additional appliances as a factor of safety. In addition, BS 6465 considers the most frequently used appliances i.e. those which are usually in use during peak hours and have a significant impact on total demand flow. Meanwhile, less detail is given for other appliances such as showers and bucket sinks, as they have less effect on the maximum flow rate.

As this study deals with the oversizing problem, worst-case scenarios were also considered within the simulation. For this purpose, the data from the case study buildings was used as a basis for a sensitivity analysis to estimate the flow from appliances not mentioned in the design code, i.e. kitchen sink, bucket sink and washing machine. Figure 3-15 shows the distribution of provision of these appliances depending upon number of persons. The results show that there is one kitchen sink per seventy persons, one washing machine per two hundred persons and one bucket sink per three hundred persons. However, the number of these appliances may be affected by other factors such as floor area and number of floors. To avoid any miscount of appliances and as a factor of safety, extra numbers of these appliances were applied in the simulation as follows:

- addition of one kitchen sink for groups of less than 50 and plus one for every unit or fraction of a unit of 50 persons.
- addition of one washing machine for groups of less than 100 and plus one for every unit or fraction of a unit of 100 persons
- addition of one bucket sink for groups of less than 100 and plus one for every unit or fraction of a unit of 200 persons**.**

After setting out the provision of appliances based on the number of users for a workplace building, more than 400 numbers of users were generated comprising 10 to 2,000 persons. Similar to the tables above, the number of appliances increases with an increasing number of persons to represent increasing size of the building.

Figure 3-15 Number of kitchen sinks, bucket sinks and washing machines in the case study building with their trend lines equations

3.11 Conclusion

In order to estimate the design flow rate in buildings, different approaches have been adopted globally. Updates to design guides, introduced in part through the modification of LU values, have largely been unable to achieve the desired improvements across a wide range of building types. However, alongside this, studies based on new models have been relatively successful in achieving a better estimation of design flow. These studies have adopted different types of statistical models. In this chapter, a scientific investigation and critical assessment have been undertaken to reveal the advantages and limitations of all possible approaches. The justification for selecting the stochastic model to estimate design flow rate has been presented. Standard probabilistic models have been unable to estimate demand flow rate as accurately as desired and it is known that most of the codes originating from a probability model result in overestimation of design flow. Meanwhile, empirical approaches need a large amount of data to develop a robust model and cover all types of buildings; it is known that gathering these data is a difficult, costly and time-consuming process. Finally, the selection of a stochastic model for use in this study is based on three main reasons: i) although development of the model depends mainly on statistical information on users and appliances instead of requiring flow rate data, it can still accurately predict water demand in buildings; ii) the model can be applied to different types of buildings and be updated depending on changes in users and appliances in the future; ii) design flow rate can be calculated for different levels of reliability depending on the design requirements.

Recent successful studies on water demand estimation were also investigated. It is worth noting that the Monte Carlo technique has been used in most of these recent studies. The results obtained from using the WDC in the United States led this study to take a similar direction but in a more effective way to simulate demand flow specifically for non-residential buildings. Thus, a Monte Carlo simulation was applied to capture all possible water usages as a part of the new model.

Finally, the chapter has explained that developing a successful stochastic model requires gathering information on appliances, users, and buildings. More importantly, the decision has been made to select suitable input variables. Based on critical analysis and scientific review, the following decisions can be summarised:

a. the model will estimate demand flow for non-residential buildings and derive design equations specifically for workplace buildings
b. users will form the main variable in the final design equations
c. sanitary appliances will include: WC, hand washing taps, urinal, shower, kitchen sink, cleaning sink, and washing machine.
d. sanitary appliances will be classified in five groups (A, B, C, D, and E) based on water-efficiency levels.
e. the model will use the average flow rate, q, of each type of appliance, calculated from all appliances available in the European water label site.
f. p-values available from the CIPHE guide will be used in the model.
g. the relationship between the number of users and provision of sanitary appliances will be used to define demand.

Chapter 4 Developing a new stochastic model to estimate demand flow for workplaces

4.1 Introduction

Based on the comprehensive investigation of methods used to estimate water demand as presented in the previous chapter, development of a stochastic model was specifically selected for application in this study. This chapter hence presents a novel stochastic modelling approach developed for the estimation of water demand and one that minimises the potential risk of system oversizing. This model is referred to herein as the Water Demand Estimation Model (WDEM) for workplaces. The underpinning methodology adopted to build the model utilises a binomial function and related probability distribution to determine busy appliances during water use events. A Monte Carlo based technique is integrated within the modelling framework to capture all possible simultaneous uses of sanitary appliances. The model is shown to simulate water demand in workplaces and is successfully able to estimate the design flow rate for a range of number of users. A water labelling concept was applied to derive new design equations while accounting for the water efficiency level of the sanitary appliances. This chapter also presents the main achievement of this study by deriving new design equations that can be used to estimate demand flow in workplace buildings.

4.2 Probability distribution in water demand modelling

A probability distribution can be described as a function that defines the likelihood of possible values that a random variable can display. Water usage, like any other event, can be represented using a probability density distribution. A range of probability distributions have been previously defined for water modelling, for instance, Blokker, (2010) utilises a range of probability distributions to fit the data collected for her study, such as normal, lognormal, x^2, poisson and negative binomial. Additionally, Buchberger *et al.* (2015b, 2017) explained how binomial and Poisson distributions were employed as part of a probabilistic approach to estimate demand flow for application in the USA. They also discussed the improvement of the application of the Wistort method for small scale dwellings with small numbers of appliances and users, using the Zero-Truncated Binomial Distribution (ZTBD) instead of a standard binomial distribution. Thus, the binomial distribution can be considered the foundation for water demand estimation, especially in large buildings where there are large numbers of sanitary appliances and where stagnation during peak periods is unlikely. Buchberger *et al.* (2015b, 2017) confirmed the appropriateness of the binomial distribution to best describe the conditional probability distribution of busy sanitary appliances, especially for a large number of appliances and occupants. Thus, the application of binomial distribution was selected in the model considering that this study focuses on non-residential buildings which have relatively large numbers of sanitary appliances.

4.2.1 Binomial distribution

To model the probability distribution of water usage events, consider an experiment based on using water at any water appliance in a washroom. It is possible to repeat this process many times in which each use (trial) for any single appliance has two possible outcomes: *on* “open” or *off* “closed”, in other words, busy or idle. Depending on the frequency of use, each type of appliance has its probability of use (*p*-value), which is the probability that water is flowing, i.e. the appliance is in use. No matter how many times this experiment is repeated, the outcome of one event does not affect the outcome of the other events and *p* remains the same in all trials. Therefore, this use of water can be defined as a Bernoulli trial assuming that water usage is a binomial process considering three key points:

- the experiment/event can be repeated *n* times
- each event is independent
- using sanitary appliances has only two possible outcomes *on* or *off*

In statistical terminology, the probability that the appliance is in use (On) or failure (Off) is defined by Yamane (1973) as:

$$P(On) = p \tag{4.1}$$

$$P(Off) = 1 - p = f \tag{4.2}$$

where:

$P(On)$ is the probability that one or more appliances are open (in use) in an event

$P(Off)$ is the probability that none of the appliances are in use, i.e. all are closed in an event

p is *p*-value which is the probability that an appliance is in use

$1 - p$ is the probability that an appliance is not in use

$= f$ (failure)

In general, the probability of k number of appliances being in use out of n number of independent trials for a binomial process can be denoted as:

$$P(k) = \binom{n}{k} p^k f^{n-k} \qquad k = 0,1, \dots . n \tag{4.3}$$

where:

P(k) is the probability of *k* number of appliances being in use out of *n* in a water use event

n is the number of appliances of the same type

k is the number of appliances in use out of *n* number of the same type

p is *p*-value which is the probability that the appliance is in use

f is the probability of not using this specific appliance

$\binom{n}{k}$ is the number of combinations in which *k* numbers of appliances are in use out of the total number of appliances *n,* calculated from the following equation:

$$\binom{n}{k} = \frac{n!}{k!\,(n-k)!} \tag{4.4}$$

Note: the total number of combinations can be calculated using the following equation:

$$\text{Total numbers of combinations} = 2^{\,n} \tag{4.5}$$

The $P(k)$ in Equation 4-3 can also be expressed as Equation 4-6 in which the b represents binomial, and this expression shows explicitly the two parameters n and p. n is the number of Bernoulli trials (number of appliances in a trial), k is the random variable (number of appliances in use).

$$P(k) = b(k; n, p) \tag{4.6}$$

4.2.2 Calculating total demand flow rate

Each water use event has a different likelihood of use of the appliances which will result in a different demand flow. To capture simultaneous use of mixed appliances and calculate total flow rate, it is also necessary to determine the probability of all combinations of appliance use. Herein, the demonstration by Omaghomi and Buchberger (2014) and Buchberger *et al.* (2017) can be cited. To explain the calculation, consider three types of appliances in a washroom: 2 basin taps, 3 WCs and 1 shower with a total number of 6, with different flow rates and *p*-values as shown in Table 4-1. In order to calculate total flow rate, all possible outcomes for simultaneous use of all appliances should be considered. Depending on the number of open appliances, i.e. the number of appliances in use, Equations (4-4) and (4-5) can be used to calculate the number of possible combinations for each event and the total number of respective combinations, as shown in Table 4-2. To explain the number of combinations, Table 4-3 shows some of the 64 possible outcomes of combinations of using six appliances.

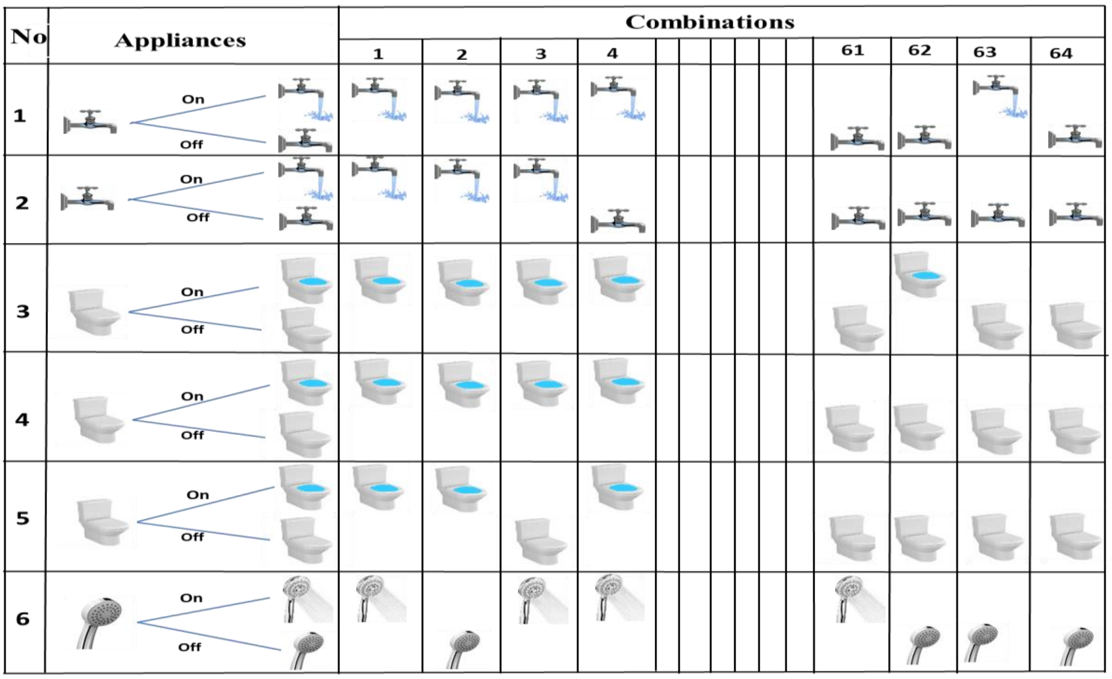
Table 4-1 Example of a washroom with appliances and their parameters

Groups (g)	**Appliances**		**Symbol**	***p*- value**	**Number (n)**	***q* l/m**	**q_a l/m**
1	**Basin tap**		B	0.055	2	9	18
2	**WC**		W	0.1	3	6	18
3	**Shower**		S	0.167	1	5	5
			Total		6		41

Table 4-2 Number of combinations for a group of six appliances using equation 4-4 & 4-5

k	No of combinations
0	1
1	6
2	15
3	20
4	15
5	6
6	1
Total	**64**

Table 4-3 Combinations of busy appliances for three groups of six appliances



The estimation of demand flow for this simple case requires analysis of the water use events for all 64 combinations with a determination of the corresponding probability of each event. Thus, selecting total demand flow for use as the design flow rate requires certain considerations: calculating flow rate based on simultaneous use of the appliances and probability of occurrence.

In the above example, total flow rate can be calculated based on busy appliances in each combination and is simply the sum of flow rate for all busy appliances using Equations 4-7 and 4-8.

$$q_a = k * q \tag{4.7}$$

$$q_t = \sum_{g=1}^{g} q_a \tag{4.8}$$

where:

q_a is the total flow rate of all appliances of the same type in a water use event
q_t is the total flow rate of all mixed appliances in the water use event
g is the number of appliance groups (types), in this example 3: “tap, WC and shower”
q is the flow rate of each appliance
k is the number of appliances in use out of n number of the same type

Below are examples of calculating total flow rate for some of the combinations:

- when all appliances are closed, i.e. 0 appliances in use: k=0, there is only one outcome which is: [0 B, 0 W, 0 S] ð q_t = (0) *9 + (0) * 6 + (0) * 5 = **0** *l/m*

- when all appliances are open, i.e. 6 appliances in use: k=6, there is only one outcome which is: [2B, 3 W, 1S] ð q_t = (2) *9 + (3) * 6 + (1) * 5 = **41** *l/m*

- with changing number of appliances in use, the number of possible outcomes will increase as shown in Table 4-3. For instance, for k=3 there are 20 possible outcomes of which the following are examples:

  - k=3: [2B, 1 W, 0S] ð q_t = (2) * 9 + (1) * 6 + (0) * 5 = **24** *l/m*

  - k=3: [0B, 3 W, 0S] ð q_t = (0) * 9 + (3) * 6 + (0) * 5 = **18** *l/m*

  - k=3: [1B, 1 W, 1S] ð q_t= (1) * 9 + (1) * 6 + (1) * 5 = **20** *l/m*

- k=3: [1B, 2 W, 0S] ð q_t = (1) * 9 + (2) * 6 + (0) * 5 = **21** *l/m*
- k=3: [0B, 2 W, 1S] ð q_t = (0) * 9 + (2) * 6 + (1) * 5 = **17** *l/m*

The results show that the total flow rate starts from zero, when no appliances are in use, to a maximum of 41 *l/m* when all appliances are in use. It can also be seen that when three appliances are in use, the total flow rate is not the same for all combinations, but different values are obtained depending on the combination. Therefore, it is essential to calculate flow rate for all 64 combinations in order to determine all possible flow rates. Despite this approach being able to determine total flow rate for all possible simultaneous uses of the appliances, it is not clear how often these values are repeated. Thus, it is not possible to decide which one can be used for design flow rate without considering the probability of each outcome.

4.2.3 Probability of water use events in water demand estimation

Calculating total demand flow alone does not provide enough information to make a decision on design flow rate; therefore, it is necessary to find its probability and select an acceptable level of confidence. The probability of any water usage event for mixed appliances can be determined by either application of a binomial equation or enumeration of all outcomes.

As explained in the previous section, Equation 4-3 can be used to calculate probability of using *k* number of appliances out of *n*. This can be applied for a specific type of appliance with the same *p*-value, while it is necessary to use the average *p*-value when there are mixed appliances. In this case, approximate probability P' can be calculated using the binomial equation 4-3 but with average *p*-value and total number of mixed appliances which can be written as:

$$P'(K) = \binom{N}{K} p'^{K} f'^{N-K} \qquad K = 0,1, \dots . N \tag{4.9}$$

where:

P'(K) is the approximate probability of *K* number of mixed appliances (in different types) in use out of *N* total number of mixed appliances in a water use event

N is total number of mixed appliances (different groups)

K is number of mixed appliances that are in use (different groups)

p' is the average *p*-value of all mixed appliances

f' is the average probability of not using these appliances

For the previous example, the average *p*-value p' can be calculated from Table 4-1 as following:

$$p' = \frac{p_B + p_W + p_S}{3} = \frac{0.055+0.1+0.167}{3} = 0.107$$

Then, by applying p' in Equation 4-9, the approximate probability for the combinations can be determined, with calculations of these combinations including:

- when all appliances are closed, i.e. 0 appliances in use: *K*=0:

$$P'(0) = \binom{6}{0} p^0 f^{6-0}$$

$$P'(0) = \frac{6!}{0!\,(6-0)!}(0.107)^0(1-0.107)^{6-0}$$

$P'(0)$= 1 (1) (0.5679) = **0.507**

- when all appliances are open, i.e. 6 appliances in use: *K*=6:

$$P'(6) = \binom{6}{6} p^6 f^{6-6}$$

$$P'(6) = \frac{6!}{6!\,(6-6)!}(0.107)^6(1-0.107)^{6-6}$$

$P'(6)$= 1 (0.0000015) (1) = $\mathbf{1.5*10^{-6}}$

- when three appliances are open, i.e. 3 appliances in use, any combination of the 20 outcomes, *K*=3:

$$P'(3) = \binom{6}{3} p^3 f^{6-3}$$

$$P'(3) = \frac{6!}{3!\,(6-3)!}(0.107)^3(1-0.107)^{6-3}$$

$P'(3)$= 20 (0.001225) (0.712122) = **0.0192**

The other method which can be used to calculate exact probability for each outcome is enumeration of all outcomes, using Equation 4-10:

$$P(K) = \prod_{g=1}^{g} p^k f^{n-k} \qquad k = 0,1, \ldots . n \qquad (4.10)$$

where:

P(K) is the exact probability of *K* number of mixed appliances (of different types) in use out of *N* total number of mixed appliances in a water use event

K is total number of mixed appliances in use (different groups)

n is the number of appliances of the same type

k is the number of appliances in use out of *n* number of the same type

p is *p*-value which is the probability that the appliance is in use

f is the probability of not using this specific appliance

Citing the previous example, the exact probability of each combination can be calculated from Equation 4-10, which can be written as follows for the group of appliances B, W, and S:

$$P\,(K) = [(p_B)^k\,(f_B)^{n-k}\,] * [(p_W)^k\,(f_W)^{n-k}\,] * [(p_S)^k\,(f_S)^{n-k}\,]$$

- when all appliances are closed, i.e. 0 appliances are in use: *K*=0:

$$P\,(0) = [(p_B)^0\,(f_B)^{2-0}\,] * [(p_W)^0\,(f_W)^{3-0}\,] * [(p_S)^0\,(f_S)^{1-0}\,]$$

$P(0) = [(f_B)^2] * [(f_W)^3] * [(f_S)^1]$

$P(0) = [(1 - 0.055)^2] * [(1 - 0.1)^3] * [(1 - 0.167)^1]$

$P(0) = (0.945)^2 (0.9)^3 (0.833)^1 =$ **0.542**

- when all appliances are open, i.e. 6 appliances in use: *K*=6:

$P(6) = [(p_B)^2 (f_B)^{2-2}] * [(p_W)^3 (f_W)^{3-3}] * [(p_S)^1 (f_S)^{1-1}]$

$P(6) = [(p_B)^2] * [(p_W)^3] * [(p_S)^1]$

$P(6) = [(0.055)^2] * [(0.1)^3] * [(0.167)^1]$

$P(6) = \mathbf{0.0000005 = 5.05*10^{-7}}$

- when 3 appliances are open, i.e. 3 appliances in use: *K*=3, in this case the combination should be specified as there are 20 outcomes, an example of which is [2B, 1 W, 0S]:

$P(3) = [(p_B)^2 (f_B)^{2-2}] * [(p_W)^1 (f_W)^{3-1}] * [(p_S)^0 (f_S)^{1-0}]$

$P(3) = [(p_B)^2] * [(p_W)^1 (f_W)^2] * [(f_S)^1]$

$P(3) = [(0.055)^2] * [(0.1)^1 (1\text{-}0.1)^2] * [(1\text{-}0.0.167)^1]$

$P(3) =$ **0.0002**

In this simple example, to meet the maximum demand with no failure, a flow rate of 41 *l/m* was calculated when all appliances were open (*K*=6). Meanwhile, calculation of probability of this event (exact and approximate probability) showed that the chance of this event occurring is very small, with a probability of only 0.0000005. Thus, the use of a ‘no failure’ condition, i.e. 100th percentile, would result in an oversizing of the water system. This is the reason behind most design guides using the 99th percentile for calculating design flow rate.

It is also important to note that using approximate probability does not consider all combinations of simultaneous use of the sanitary appliances. The exact probability, therefore, is preferable in water demand modelling as probability of all combinations can be considered. However, whilst the procedure of calculating the exact probability is straightforward in principle when the number of appliances is small, it is not practical when the number of appliances is large because the number of possible outcomes grows exponentially with the increasing number of appliances. Combinatorial explosion in the number of combinations in large buildings renders this approach impractical; for example, the number of combinations of groups of appliances of 10, 15 and 20 will be 1,024, 32,768 and 1,048,576, respectively. Therefore, it is impossible to analyse all outcomes for large buildings, especially non-residential buildings where there are usually large numbers of sanitary appliances.

This analysis confirms the need for an alternative approach, such as using binomial distribution with Monte Carlo technique, to estimate demand flow with corresponding probabilities without the enumeration of all possible outcomes.

4.2.4 Monte Carlo technique

The Monte Carlo technique, which is now extensively used in many scientific studies, can be defined as a mathematical technique that relies on repeated random sampling to model the probability of different outcomes and to obtain numerical results using different probability distributions such as the binomial distribution (Thomopoulos, 2013).

In this study, using the Monte Carlo technique is key for developing the water demand model as: firstly, for a large number of appliances, enumeration is not practical because of the exponential growth of the size of combinations. Using a Monte Carlo simulation helps to capture all possible outcomes without the need to analyse the outcomes individually. Secondly, the binomial equation is used for determining the number of busy appliances instead of the probability of the events, i.e. assuming probability to find corresponding busy appliances. Existing infinite values of probability between 0 and 100% made the calculation very challenging, while application of Monte Carlo technique and coding on a powerful software made the simulation both possible and successful. In other words, obtaining accurate flow rates with their corresponding probabilities would be impossible without using the Monte Carlo technique.

It should be noted that the Monte Carlo simulation depends mainly on a number of repetitions and therefore requires the use of powerful computing software. Programming this simulation using MATLAB has allowed the model to run thousands of repetitions and set a stable estimate of the corresponding frequency of busy appliances. Running the model in this way to generate CDFs of flow rate replicates water usage events that are very close to actual usage and also results in a much more accurate estimation of flow rate.

4.3 Developing WDEM: requirements and considerations

Unlike current design methods which mostly focus on residential buildings, the WDEM can be described as a novel approach to estimate design flow rate specifically for non-residential buildings. Before explaining how the model works, it is essential to discuss the criteria and parameters used for its development. Decisions on input variables and model boundaries are crucial to obtain a successful outcome and ensure the model represents the modern plumbing system. The model can be defined as reflecting a combination of the interaction between users and the provision of appliances alongside the generation of a wide range of probabilities to capture all possible simultaneous uses of sanitary appliances. Thus, the model relies on establishing a range of building sizes from small to large scale which requires allocating the provision of sanitary appliances based on the number of users. In addition, applying a binomial distribution to create a random probability model and capture all possible water use events necessitates information about all sanitary appliances. The following sections provide details of these considerations and the parameters used in the model.

4.3.1 Number of trials (T_r)

One of the distinctions of the WDEM is its use of a Monte Carlo simulation which enables the model not only to capture all possibilities of appliance use, but also to consider how often each event occurs. Thus, the model uses random numbers of probability, *P*, to determine the number of appliances in use, *k*. If the simulation were run for small numbers, it would be impossible to capture all combinations of simultaneous use, and the differences between results would be relatively large. Accurate estimation of demand flow depends mainly on the number of trials or sample size to capture all possible simultaneous uses of the sanitary appliances. In general, this type of simulation requires to be run at least a couple of hundred thousand times to obtain a stable result and to minimise the difference between outcomes. In this approach, it is assumed that if the simulation were run for an infinite number of times, the difference in results would be zero. Of course, it is impossible to run the simulation infinite times, but with contemporary computing ability, the simulation can nonetheless be run many hundreds of thousands of times using programs such as MATLAB.

For small scale buildings such as the Estates building, a sample size greater than 200,000 provides a good result with only one decimal point difference between outcomes. Meanwhile, larger buildings such as the Hugh Nisbet building require the simulation to be run over 300,000 times to achieve a good result. In general, the best results were obtained when the sample size was greater than 300,000 for buildings up to 2,000 people. As the WDEM was designed to estimate demand flow rate in any size of building (even in buildings with more than 2,000 people), the model was coded to run the simulation 400,000 times. This size of sample helped the model, first, to capture all possible combinations of water usage events in large scale buildings and, second, to produce stable outcomes of flow rate with differences less than 0.1 *l/s*.

In order to illustrate the impact of sample size on a Monte Carlo simulation, the estimation of the value of π as an example is discussed below. It is possible to estimate the value of π by creating a random sample to cover both areas: area of the circle (A1) and the square (A2), Figure 4-1, with boundary (-1 to +1) as shown below:

Area of the circle A1 = $\pi\, r^2$

Area of the square A2 = $2r * 2r = 4r^2$

$$\frac{A1}{A2} = \frac{\pi\, r^2}{4\, r^2} = \frac{\pi}{4}$$

$$\boldsymbol{\pi} = \frac{4\,A1}{A2} = \frac{4 * no\ of\ points\ inside\ the\ circle}{Total\ no\ of\ points\ inside\ the\ square}$$

Three sets of random values of x=random ($-1 \geq x \geq +1$) and y= random ($-1 \geq y \geq +1$) were generated and plotted as the following:

a) When the sample size is only 1000, the number of points in A1=740 and A2= 1000:

$$\boldsymbol{\pi} = \frac{4\ (741)}{(1000)} = 2.964$$

b) When the sample size is 10, 000, the number of points in A1=7,905 and A2= 10,000:

$$\boldsymbol{\pi} = \frac{4\ (7{,}905)}{(10{,}000)} = 3.1620$$

c) When the sample size is 100, 000, the number of points in A1=7,905 and A2= 10,000:

$$\boldsymbol{\pi} = \frac{4\ (78{,}438)}{(100{,}000)} = 3.13752$$

The results of estimated values of , original value of $\boldsymbol{\pi}$ and the differences are summarised in Table 4-4. The results clearly show how the sample size affects the accuracy of the outcome. The difference between the two values of $\boldsymbol{\pi}$ was reduced from 0.17759 for a sample size of 1,000 to only 0.00407 when the sample size was 100,000.

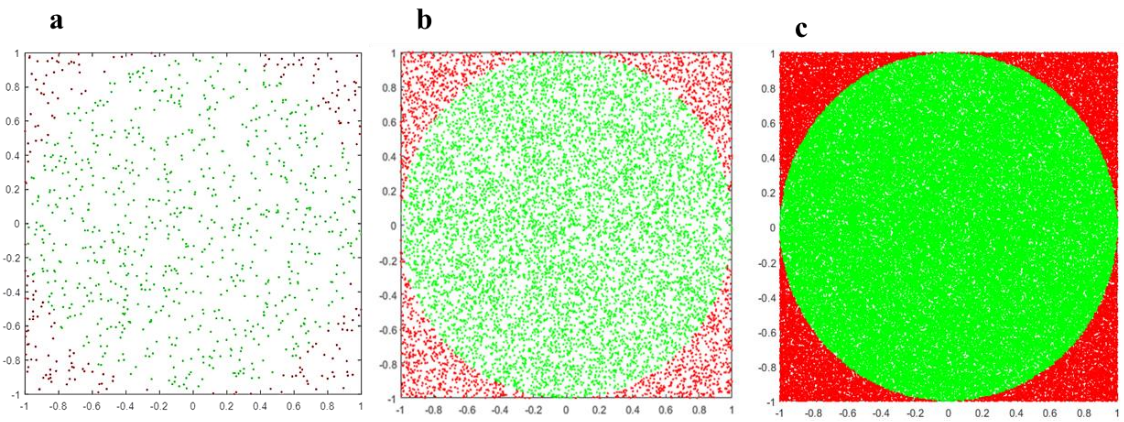


Figure 4-1 Areas of the circle and square when the sample size is a) 1000, b)10 000, and c)100 000

Table 4-4 Estimated π for sample size 1000, 10 000 and 100 000

Cases	π	Estimated π	$\Delta\ \pi$
a	3.14159265	2.964	0.17759
b	3.14159265	3.1620	0.02040
c	3.14159265	3.13752	0.00407

4.3.2 Number of users and corresponding provision of appliances

After making decisions on the building type and selecting the workplace, the first stage to be built into the model is confirmation of the number of users and the link between users and the provision of sanitary appliances. The details underpinning these relationships were outlined in section 3.10. Specifying the users is a crucial feature of the model as the number of users can be defined as the most influential factor in water demand modelling. Furthermore, the generation of a wide range of user-appliance relationships helps to derive design equations for workplaces of different size. Thus, demand flow can be simulated to cover all scales of workplaces, from small to large scale buildings. The specification of users also helps to reduce the number of variables in the final design equations; instead of inputting *p, q & n* values for each group of appliances, only the number of users, *X,* is required to calculate design flow. Moreover, it is worth mentioning that the design of the number and type of appliances was originally based on the number of persons in the building; hence, assuming provision of appliances based on number of users in the simulation enables the model to cope with unnecessary appliances that may exist in the building for any reason, such as architecture and designer judgment or installation of extra appliances to meet future demand.

The WDEM model is programmed to automatically calculate the provision of appliances for a wide range of number of users depending on the information available in BS 6465. It is also possible to calculate each appliance’s provision separately, then add to the model. Table 4-5 is an example of the calculations of sanitary appliances on an Excel sheet based on number of persons in the building.

Table 4-5 Calculation of number of users-provision of appliances

BS 6465-1+A1:2009																
Range of person	Male	Male provision			Female	Female provision		Total no.of persons	Male+Female			other appliance				Total no
		WC	HWB	Urinal		WC	HWB		WC	HB	U	Sh	BuSi	sink	WM	
																476,507
1 to 5	1	1	1	1	1	1	1	**2**	2	2	1	1	1	1	1	8
6 to 15	6	1	1	1	6	2	2	**12**	4	3	1	1	1	1	1	11
16 to 30	16	2	2	1	16	3	3	**32**	6	5	1	1	1	1	1	15
31 to 45	31	2	2	2	31	4	4	**62**	7	6	2	1	1	2	1	19
46 to 60	46	3	3	2	46	5	5	**92**	10	8	2	1	1	2	1	24
61 to 75	61	3	3	3	61	6	6	**122**	11	9	3	2	2	3	2	30
76 to 90	76	4	4	3	76	7	7	**152**	13	11	3	2	2	4	2	35
91 to 100	91	4	4	4	91	8	8	**182**	14	12	4	2	2	4	2	38
101 to 125	101	5	5	5	101	9	9	**202**	17	14	5	3	3	5	3	47
126 to 150	126	5	5	5	126	10	10	**252**	18	15	5	3	3	6	3	50
151 to 175	151	6	6	6	151	11	11	**302**	20	17	6	4	4	7	4	58
176 to 200	176	6	6	6	176	12	12	**352**	22	18	6	4	4	8	4	62
201 to 225	201	7	7	7	201	13	13	**402**	24	20	7	5	5	9	5	70
226 to 250	226	7	7	7	226	14	14	**452**	25	21	7	5	5	10	5	73
251 to 275	251	8	8	8	251	15	15	**502**	28	23	8	6	6	11	6	82
276 to 300	276	8	8	8	276	16	16	**552**	29	24	8	6	6	12	6	85
301 to 325	301	9	9	9	301	17	17	**602**	31	26	9	7	7	13	7	93
326 to 350	326	9	9	9	326	18	18	**652**	32	27	9	7	7	14	7	96
351 to 375	351	10	10	10	351	19	19	**702**	35	29	10	8	8	15	8	105
376 to 400	376	10	10	10	376	20	20	**752**	36	30	10	8	8	16	8	108
401 to 425	401	11	11	11	401	21	21	**802**	38	32	11	9	9	17	9	116
426 to 450	426	11	11	11	426	22	22	**852**	40	33	11	9	9	18	9	120
451 to 475	451	12	12	12	451	23	23	**902**	42	35	12	10	10	19	10	128
476 to 500	476	12	12	12	476	24	24	**952**	43	36	12	10	10	20	10	131
501 to 525	501	13	13	13	501	25	25	**1,002**	46	38	13	11	11	21	11	140
526 to 550	526	13	13	13	526	26	26	**1,052**	47	39	13	11	11	22	11	143
551 to 575	551	14	14	14	551	27	27	**1,102**	49	41	14	12	12	23	12	151
576 to 600	576	14	14	14	576	28	28	**1,152**	50	42	14	12	12	24	12	154
601 to 625	601	15	15	15	601	29	29	**1,202**	53	44	15	13	13	25	13	163
626 to 650	626	15	15	15	626	30	30	**1,252**	54	45	15	13	13	26	13	166
651 to 675	651	16	16	16	651	31	31	**1,302**	56	47	16	14	14	27	14	174
676 to 700	676	16	16	16	676	32	32	**1,352**	58	48	16	14	14	28	14	178
701 to 725	701	17	17	17	701	33	33	**1,402**	60	50	17	15	15	29	15	186
726 to 750	726	17	17	17	726	34	34	**1,452**	61	51	17	15	15	30	15	189
751 to 775	751	18	18	18	751	35	35	**1,502**	64	53	18	16	16	31	16	198
776 to 800	776	18	18	18	776	36	36	**1,552**	65	54	18	16	16	32	16	201
801 to 825	801	19	19	19	801	37	37	**1,602**	67	56	19	17	17	33	17	209
826 to 850	826	19	19	19	826	38	38	**1,652**	68	57	19	17	17	34	17	212
851 to 875	851	20	20	20	851	39	39	**1,702**	71	59	20	18	18	35	18	221
876 to 900	876	20	20	20	876	40	40	**1,752**	72	60	20	18	18	36	18	224
901 to 925	901	21	21	21	901	41	41	**1,802**	74	62	21	19	19	37	19	232
926 to 950	926	21	21	21	926	42	42	**1,852**	76	63	21	19	19	38	19	236
951 to 975	951	22	22	22	951	43	43	**1,902**	78	65	22	20	20	39	20	244
976 to 1000	976	22	22	22	976	44	44	**1,952**	79	66	22	20	20	40	20	247
1001 to 1025	1,001	23	23	23	1,001	45	45	**2,002**	82	68	23	21	21	41	21	256

4.3.3 Flow rate of appliances q

Defining the flow rate of different appliances is essential in water demand modelling. Since reducing the flow rate of sanitary appliances is considered an essential part of any water conservation scheme, water-efficient appliances are typically used in current modern plumbing systems worldwide. Thus, careful analysis is required during the selection of flow rate for appliances before use within the model. As discussed in section 3.8, appliance flow rate can normally be obtained from manufacturers' specifications.

To collect information on appliance flow rate, a detailed investigation on available brands and types of sanitary appliances was undertaken using online resources. For this purpose, the information available via the European water labelling website was used to select flow rate for the sanitary appliances. This site provides information about all sanitary appliances available in Europe including the UK. One of the key features of the European labelling scheme is that all sanitary appliances are classified into five groups (A, B, C, D and E) based on their flow rate. The appliances with a flow rate less than 5 *l/m* are mostly classified as water-efficient appliances (Group A). Meanwhile, the other classifications can be applied for those appliances with a flow rate of greater than 5 *l/m*. Herein, information on more than 6000 appliances has been analysed (see section 3-8) to obtain flow rate values. Based on this data, the average flow rate for all five groups was used in the simulation.

Adopting this concept allows the model to derive design equations related to the water efficiency levels of sanitary appliances and taking into account varying types and models. It is also helpful that the new design equations will map to the sanitary appliances currently available in the UK. Table 4-6 shows the types of appliances, their average flow rate and the water efficiency levels used in the simulation. It is worthy of mention that the model was designed to enable this input variable to be changed and the simulation run for any other values of appliance flow rate.

Table 4-6 Classification of sanitary appliances and their flow rate

No	Appliances	q_{avg} l/m				
		A	B	C	D	E
1	Hand wash tap	3.7	7.1	9.1	11.6	15.0
2	WC	2.4	2.4	2.4	2.4	4.5*
3	Urinal	2.4	2.4	2.4	2.4	4.5*
4	Shower	3.7	7.1	9.1	11.6	15.0
5	Kitchen sink	4.0	7.1	9.1	11.6	15.0
6	Bucket sink	4.0	7.1	9.1	11.6	15.0
7	Washing machine	4.3	4.3	4.3	5.0	6.0

4.3.4 Probability that an appliance is in use (p-value)

The *p*-value, i.e. the probability that an appliance is in use, is another key input parameter in the WDEM. Section 3-9 provided a detailed discussion on *p*-values and the approaches for obtaining them, concluding that those available in the CIPHE code should be used in the model. The reasons behind using *p*-values from the CIPHE code are: i) this design guide is based on data specific to the UK. This means that the type of sanitary appliance, and water consumption and user behaviour patterns in the UK were considered in determining *p*-values. ii) this guide extends to cover the necessary building types in calculating *p*-values. It provides different values of *p* depending on the building type and frequency of use. Low *p*-values correspond to 20 minutes of frequency of use which is suitable for dwellings and other buildings where appliances are used by a single person or a small group. Medium *p*-values correspond to 10 minute intervals of frequency of use which is appropriate for buildings that are used by larger groups of people on a random basis and for which set time constraints are not required, such as public toilets. This category is best for workplace buildings and therefore was used in the model to estimate demand flow. High *p* values correspond to only 5 minute intervals as would be the case within buildings where the appliances are used by a large group of people over a short period of time, such as in theatres.

Table 4-7 provides information on *p*-values including the duration of time that the appliance is in use (t) and the time between successive uses (T). The *p*-value, as one of the input parameters, can be changed and updated in the model. Thus, the model users can simply apply different *p*-values and make any amendments and updates in the future. The necessary parameters for sanitary appliances used in the model are summarised in Table 4-8, including *p*-values and average flow rate of appliances.

Table 4-7 *p*-values used in the WDEM

Type of appliance	*t* *second*	*T* *second*	*p-value*
Basin, 15mm sep. taps	33	600	0.055
Basin, 2 x 8mm mix. tap	33	600	0.055
Sink, 15mm sep/mix tap	60	600	0.100
Sink, 20mm sep/mix tap	60	600	0.100
Bath,l5mm sep/mix/tap	266	2400	0.111
Bath, 20mm sep/mix tap	266	300	0.089
WC Suite, 6 litre cistern	60	600	0.100
Shower, 15mm head	300	1800	0.167
Urinal, single bowl/stall	60*	600	0.100*
Bidet, 15mm mix tap	33	600	0.055
Hand Spray, 15mm	75	1200	0.067
Bucket sink, 15mm taps	60	3600	0.017
Slop Hopper, cistern only	75	600	0.125
Slop Hopper, cistern/taps	60	600	0.100
Clothes washing m/c, dom	25	600	0.042
Dishwasher			0.005**

***** *CIPHE considered continuous flow in urinals, which was the case in the past but is no longer; therefore, the assumption that urinals have the same p as a WC of 0.100 was made here.*

****** *CIPHE provides no p for dishwashers; this was assumed to be 0.005, taken from Table 3-3*

Table 4-8 The values of *p*-value and flow rate for sanitary appliances

No	Appliances	*p*-value	q_{avg} l/m				
			A	**B**	**C**	**D**	**E**
1	WC	0.1	3.7	7.1	9.1	11.6	15.0
2	Hand wash tap	0.055	3.7	7.1	9.1	11.6	15.0
3	Urinal	0.1	2.4	2.4	2.4	2.4	4.5*
4	Shower	0.167	2.4	2.4	2.4	2.4	4.5*
5	Kitchen sink	0.1	3.7	7.1	9.1	11.6	15.0
6	Bucket sink	0.17	4.0	7.1	9.1	11.6	15.0
7	Washing machine	0.005	4.0	7.1	9.1	11.6	15.0

4.4 Running WDEM for workplace buildings

All information was programmed using MATLAB to enable the determination of sanitary appliance provision based on the number of users and flow demand for all water usage events, assuming a 99th percentile reliability to support the resultant design flow rate. This procedure was repeated for new numbers of users with new sets of appliances to calculate design flow rates for buildings with up to 2000 users. All simulated flow rates were then plotted to determine the best fit function and find the design equation. Different design equations were obtained based on water efficiency levels (A, B, C, D and E) by running the model for appliances with different flow rates. The final result was five design equations for the workplace based on number of users and considering appliance efficiency. Figure 4-2 shows an illustrative flow chart of the WDEM, and the following sections explain the step-by-step procedure with details of each stage of the model.

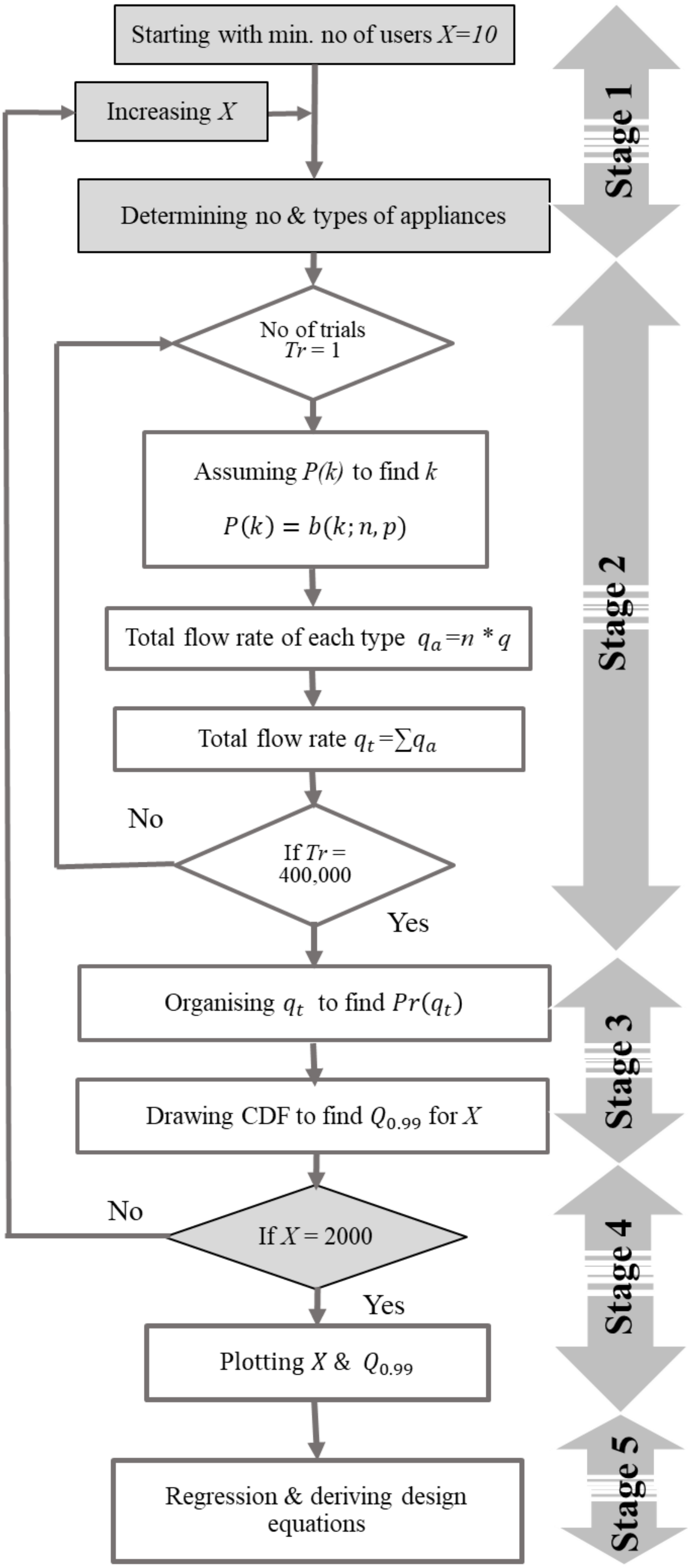


Figure 4-2 Flow chart of WDEM

4.4.1 Stage 1: Number of users and provision of sanitary appliances

The first stage of the model, indicated by the grey colour in Figure 4-1, is allocation of the number of users and establishment of the link between users and the provision of sanitary appliances in workplaces. The main input variable in this stage is the initial number of users (X) and increment rate (difference between two values of number of users). The first value of X=10 was assumed to start the simulation with a user increment rate of 30 until 200 persons, and then a user increment rate of 50 for the remainder. Applying these numbers of users and increment rates was based on BS 6465 (section 3.10) to determine the provision of appliances as recommended in the standard. After running the simulation and determining the flow rate for X=10 users and the corresponding group of appliances, a new number of users (X=10+30) was applied to the model to determine new groups of appliances and then calculate a new design flow rate. This process was repeated for different numbers of users to determine demand flow for a range of users up to X=2000. It is possible to run the model for any number of users (more than 2000), while herein flow rate was simulated for buildings with up to 2000 persons as measured flow rate data is only available for buildings with up to 1200 occupants. This means the flow rate data used for validation of the model was available for buildings with occupancy ranging from 50 to 1200 persons as discussed in detail in Chapter 5.

This part of the calculation was coded individually in the model to calculate the provision of appliances automatically based on the number of users. Alternatively, it is possible to manually input the number and types of appliances for a specific case and estimate demand flow. For instance, the model was run for the case study buildings and considered the exact number and types of appliances to estimate demand flow.

4.4.2 Stage 2: Determining total flow rate for each number of users

After setting out the first group of users ($X=10$) and determining the corresponding provision of sanitary appliances, the second section of the model provides the calculation of flow rates for all possible combinations of simultaneous use of the appliances. In this stage, the binomial equation, Equation 4-6, has been applied with the previously defined variables (n and p) to find the number of appliances that are in use, k. By applying the Monte Carlo technique, random probabilities, P, from zero to 100% were established to determine the corresponding number of busy appliances, *k*. Thus, the input parameters of *n*, *p*, and *P* were applied to the simulation to determine *k*.

Once the number of busy appliances, *k*, had been determined, the total flow rate of all the busy appliances of the same type, q_a, was calculated using Equation 4-11. In the same way, q_a was calculated for all other types of appliances, i.e. all seven types of appliances. Then the total flow rate for this group of appliances (mixed appliances) was calculated by summation of all flow rates in this water use event, Equation 4-12.

A repetition technique based on 400,000 Monte Carlo runs was applied to capture all possible water use events with their corresponding flow rate. Running the Monte Carlo model up to 400,000 times enables the simulation to be stable and minimises the difference between flow rate values, i.e. the difference between the new results and previous results become very close to zero. It is impossible to get an accurate estimation of demand flow without running the simulation many times to capture all possible simultaneous uses of the appliances. The final results consisted of a wide range of flow rate data obtained from different combinations of water usage events for this specific number of users. As the model was run 400,000 times, the outcomes were 400,000 values of q_t among which most were repeated several times.

$$q_a = \begin{cases} 0 & for \quad k = 0 \\ q * 1 & for \quad k = 1 \\ \vdots & \quad\quad \vdots \\ q * n & for \quad k = n \end{cases} \tag{4.11}$$

$$q_t = \sum_{1}^{7} q_a \tag{4.12}$$

where:

q_a is total flow rate for all appliances of the same type

q is an individual flow rate for each appliance

k is number of appliances in use of the same type

n is total number of appliances of the same type

q_t is total flow rate for all types of appliances, i.e. for all seven types

4.4.3 Stage 3: Producing provability distribution and cumulative distribution function CDF

Initial results yield a large number of flow rate values for the first number of users and the related provision of appliances. The flow rate values range from zero when no appliance is in use to a maximum when all appliances are in use. These values of flow rate were organised randomly without knowing how often each value would be repeated. At this stage, therefore, each value of flow rate was counted to determine its probability P_r in the simulation. The probability of any value of flow rate $P_r(q_{Tr})$ occurring among all flow rate data can be calculated from the following equation:

$$P_r(q_{Tr}) = \frac{number\ of\ times\ of\ occurence\ of\ q_{Tr}}{Total\ no\ of\ all\ q_t} \tag{4.13}$$

Thus, the probability of each value of q_t occurring was calculated based on its frequency in the simulation.

The flow rate data obtained from the binomial distribution can be defined as discrete variables in which there are a countable number of outcomes with separation between these outcomes. Because the 99^{th} percentile among these outcomes is required for the new design flow rate, a normal distribution was used to approximate the binomial probability in the simulation. In order to statistically check the application of the normal approximation to the binomial distribution for the flow rate data, the kstest (Kolmogorov-Smirnov) was used in MATLAB. Obtaining results of (*h* = *0*) confirmed the approximated binomial distribution at the 5% significance level. In addition, for the purposes of visual comparison, the binomial distribution (histogram) from 400,000 Monte Carlo simulations and the standard normal distribution (bell curve) were plotted in the same figure. Figure 4-3 shows good agreement between the probability distributions from flow rate data and the probability distribution function of normal distribution for three different scenarios where the number of users (*X*) are 450, 1,200 and 2,000.

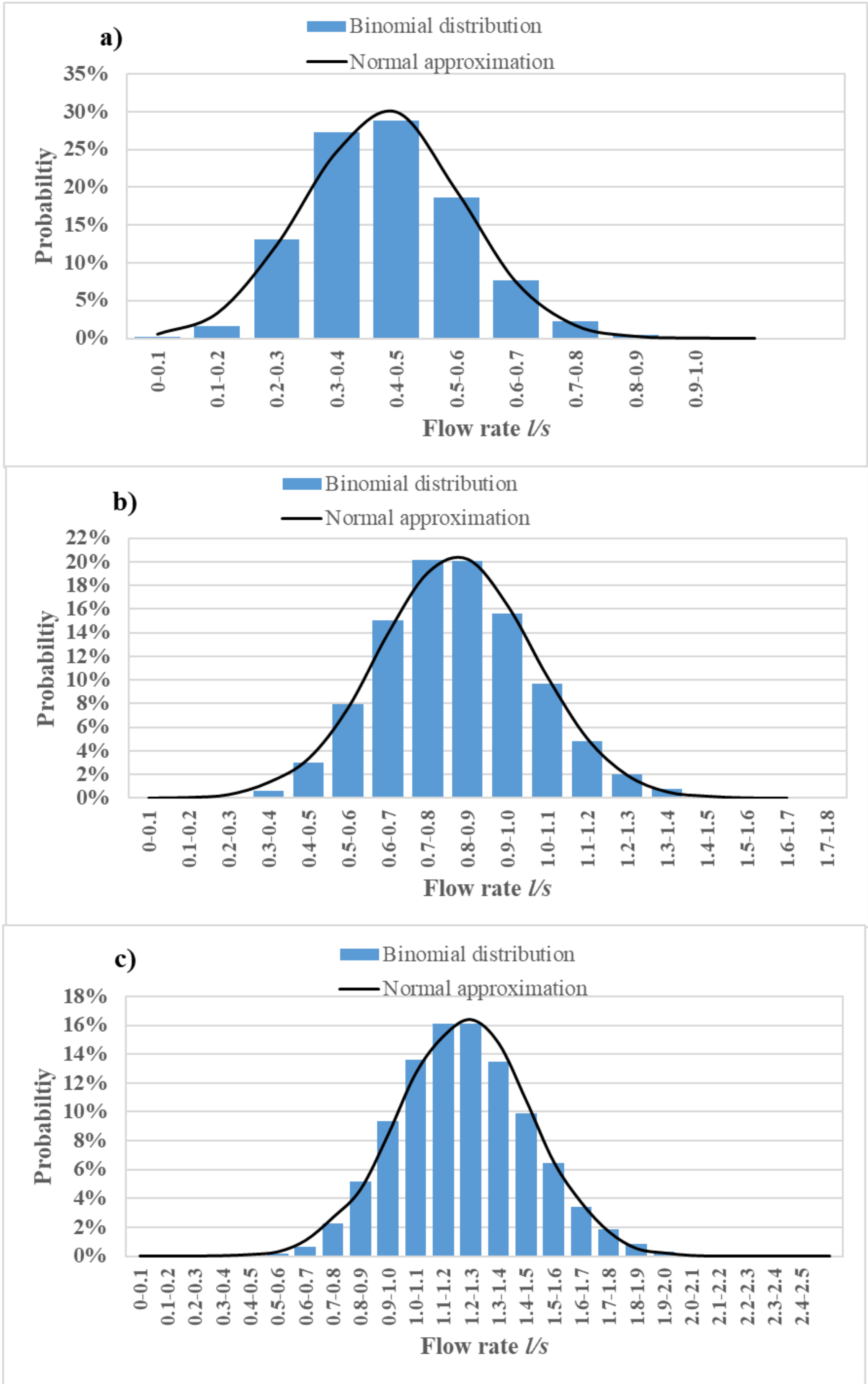


Figure 4-3 Binomial distribution and normal approximation of flow rate data for number of users a) 450, b)1,200 and c)2,000 users

After validation of the approximation of the binomial distribution using a normal distribution, the flow rate values, $q_{t,}$ and their probabilities, $P_{r,}$ were plotted to generate a Cumulative Distribution Function CDF. The full CDF for all flow rates was then used to determine simulated flow rate for the entire range of reliability of the system, i.e. from 0% to 100%. Thus, for any desirable values of reliability, simulated flow rate Q can be extracted from the CDF, for example, 99th percentile, Q_{99} .

In this study, the 99th percentile of flow rate, Q_{99}, was extracted from the CDF and considered as the design flow rate, Q_d. The use of the 99th percentile has been found to help in comparing the simulated flow rate with the flow rate obtained from the current design guides as most design approaches have used this level of confidence to design water systems. The WDEM is designed to allow changes to be made and calculation of design flow rate for any level of reliability in the future. Figure 4-4 is an example of the corresponding CDF of all flow rate values produced from 400,000 Monte Carlo runs and extraction of the 99th percentile flow for one of the case study buildings (Postgraduate Centre).

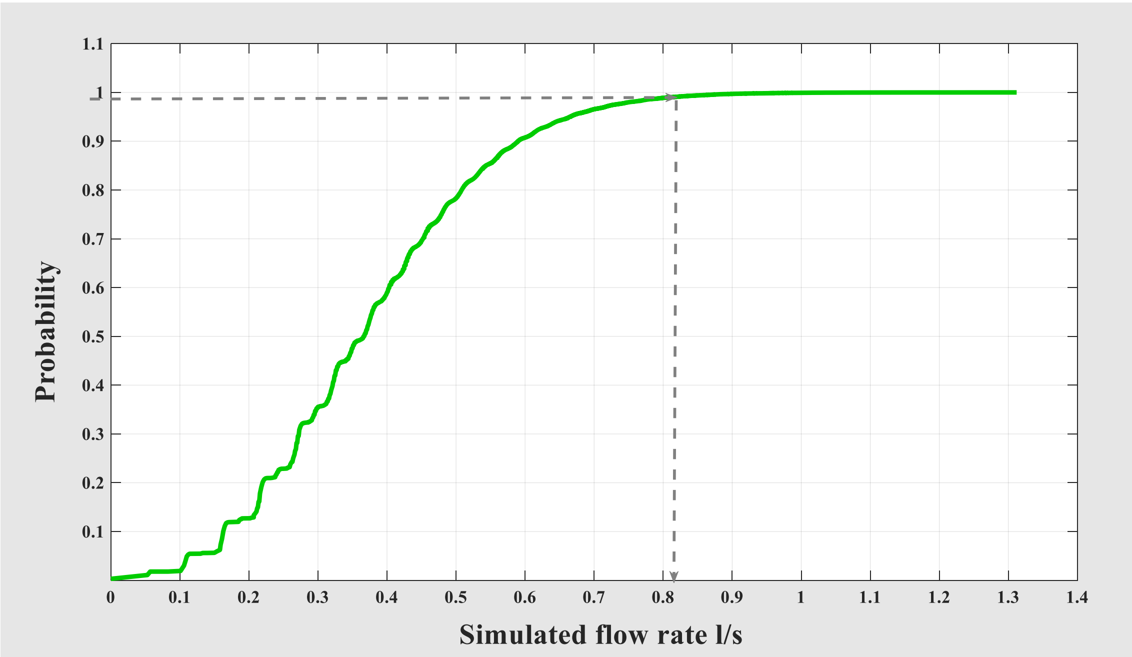


Figure 4-4 An example of CDF and extraction of 99th percentile of simulated flow rate

4.4.4 Stage 4: Number of persons-design flow rate relationship

By extracting the Q_{99} value from the CDF, the first design flow rate was obtained for the first number of users, i.e. X=10. Then the model returns to the beginning to increase the number of users and repeat the previous steps to calculate the flow rate for a new group of appliances. In the same way, a new value of design flow rate was obtained from the new CDF based on the new number of users.

In each loop, the number of users was increased depending on BS 6465. The standard provides different provisions of appliances for different numbers of users up to 100 persons, then provides a regular increasing of provision for every 25 males and 50 females. Therefore, the model was coded to increase X by 50 persons (25 males and 25 females) each time when X >200. The final outcome, thus, was a set of simulated flow rate data (Q_{99}) which were considered as design flow rates for a range of users.

It is worth noting at this stage that the same value of appliance flow rate, q, has been used in the simulation for all groups of users, i.e. the model was initially run for sanitary appliance group A. Although most appliances used in the modern plumbing system can be classified as water-efficient (group A), the level of efficiency may still be different. Therefore, the WDEM was run for all five groups of appliances using the flow rate data shown in Table 4-8 to yield five datasets based on different water-efficiency levels. Figure 4-5 shows simulated flow rates as a function of the number of persons in the workplace for all groups of appliances, i.e. A, B, C, D and E.

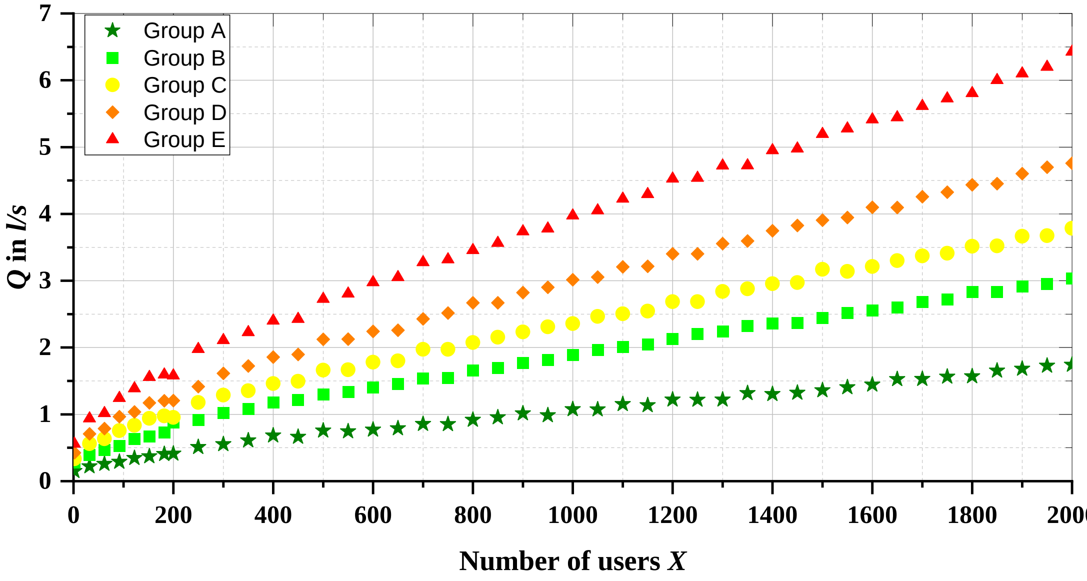


Figure 4-5 Simulated flow rates Q_{99} according to number of users

4.4.5 Stage 5: Regression and establishing design equations

Once all the values of flow rate were plotted as a function of the number of users, a regression analysis was undertaken to specify the best fit functions for the datasets. As each group of sanitary appliances had different patterns of demand flow, a specific relationship was defined for each group.

It can be seen that the values of design flow rate increase with increasing the number of persons in the buildings. Therefore, in the initial stage of the regression analysis, a single linear function was considered. Figure 4-6 illustrates the fitted line for datasets of all groups of appliances. The design equations and the values of R-squared (the coefficient of determination) are summarised in Table 4-9. The results show that for all the groups' datasets, the linear reciprocal model appears not to fit the data particularly well, especially between 0-200 persons. The different patterns before and after point 200 persons result from the difference in provision of appliance for X <200 and X>200 person recommended by the BS 6465. In order to avoid this problem and to apply the best fit function to the data, two different applications were undertaken in the regression analysis, namely curve-fitting and segmented regression.

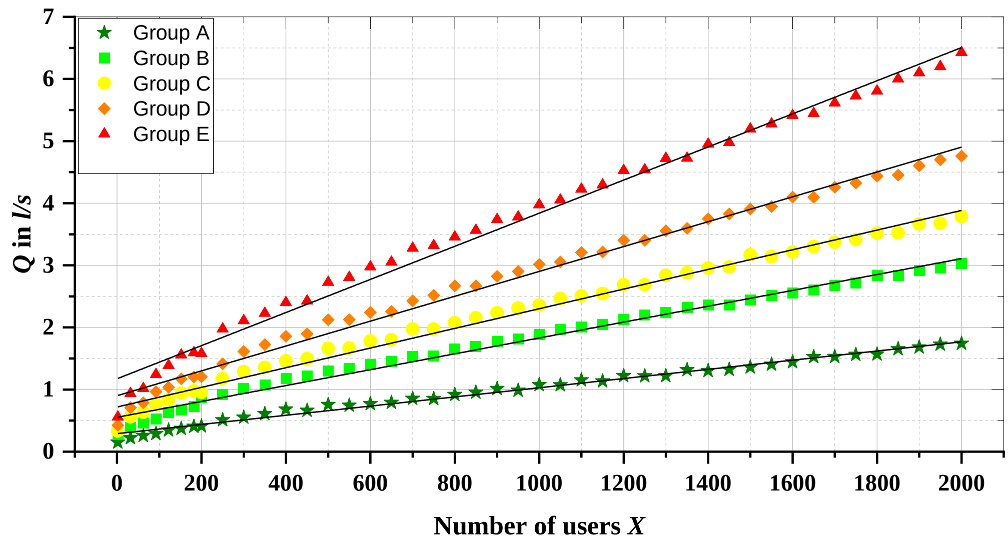


Figure 4-6 The best fit single line for the flow rate data

Table 4-9 Design equations and R-squared values for single line fit

No	Groups	Equations	R^2
1	A	Y= 0.2905+ 0.0007389 X	0.9890
2	B	Y= 0.55368+ 0.00128 X	0.9875
3	C	Y=0.71889+0.00158*X	0.98852
4	D	Y=0.90079+0.002*X	0.98864
5	E	Y=1.17419+0.00267*X	0.98961

In non-linear relationships, the change in the dependent variable (*Q*) associated with a one-unit shift in the independent variable (*X*) is dependent on the location in the observation area, i.e. the effect of the independent variable may not be a constant value. For this purpose, a second-order polynomial function was applied to find the best fit curve. Figure 4-7 shows the application of a polynomial model to mathematically define the relationship between the number of users and design flow rate. The resultant equations and their values of R-squared are summarised in Table 4-10. The table shows that the application of this approach produces better results than the linear fit and the values of R-squared are greater than 0.993.

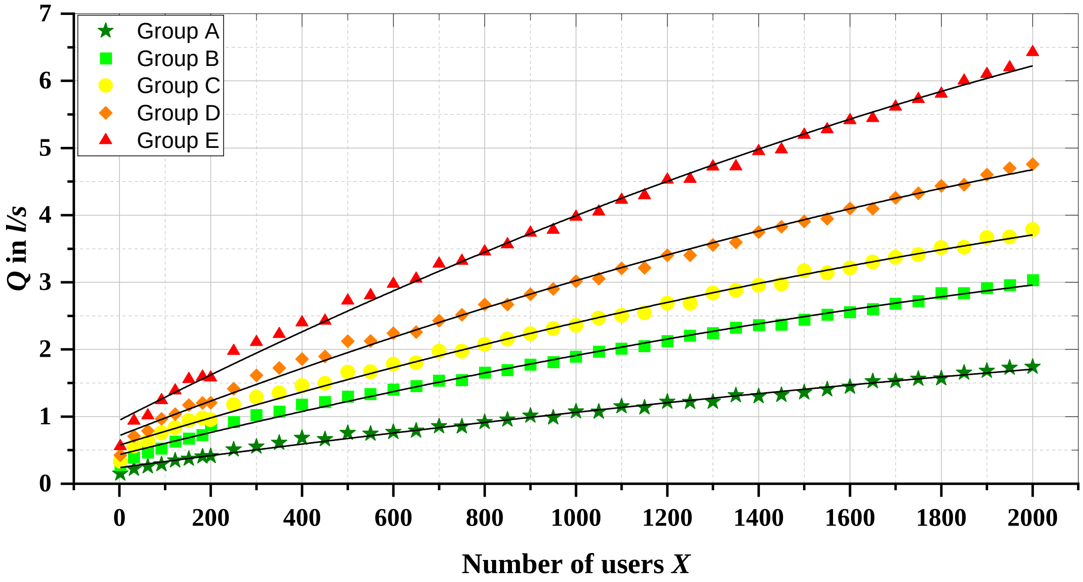


Figure 4-7 The best fit of polynomial function for the flow rate data

Table 4-10 Design equations and R-squared values for polynomial function fit

No	Group	Equations	R^2
1	A	$Y= 0.2402+ 9.13315E^{-4} X - 9.02109 E^{-8} X^2$	0.99305
2	B	$Y= 0.23429+ 0.00169 X – 2.1405 E^{-7} X^2$	0.9951
3	C	$Y= 0.57506+ 0.00208X – 2.5786 E^{-7} X^2$	0.99567
4	D	$Y= 0.71823+ 0.00263 X – 3.27302 E^{-7} X^2$	0.99584
5	E	$Y= 0.94698+ 0.00345 X – 4.07365 E^{-7} X^2$	0.9959

Another approach to determine the best fit is application of a segmented (piecewise) approach which can be used to split the original scatter plot into pieces and fit a separate line segment to each interval. As the data clearly shows that the trend changes at X=200, it is possible to split the datasets into two equations at a point between 200 & 400 and fit two separate lines. Figure 4-8 shows that the estimated two lines, connected at X=300, appear to fit much better to the datasets, with R-squared values greater than 0.997. Table 4-11 includes the design equations and the R-squared values for the segmented regression.

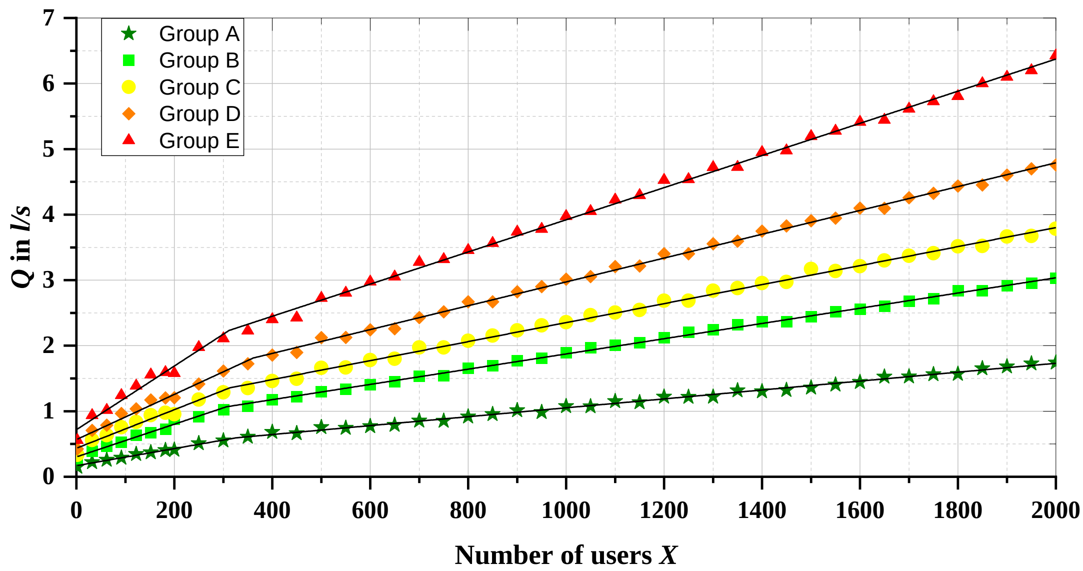


Figure 4-8 The best two-line (piecewise) fit for the flow rate data

Table 4-11 Design equations and R-squared values for two- line fit (piecewise fit)

No	Groups		Equations	R^2
1	A	$X<300$	Y= 0.16922+ 0.0013 X	0.99765
		$X\geq300$	Y= 0.37287+ 0.000679418 X	
2	B	$X<300$	Y= 0.30309+ 0.0029 X	0.99905
		$X\geq300$	Y= 0.71192+ 0.00116 X	
3	C	$X<300$	Y=0.45351+0.00294*X	0.99833
		$X\geq300$	Y=0.90254+0.00145*X	
4	D	$X<300$	Y=0.56724+0.00345*X	0.9986
		$X\geq300$	Y=1.1554+0.00182*X	
5	E	$X<300$	Y=0.71824+0.00486*X	0.99841
		$X\geq300$	Y=1.46805+0.00245*X	

After undertaking the regression analysis and plotting the linear and non-linear functions for the flow rate data, a comparison between the R-squared values was undertaken to assess the application of single line, polynomial and piecewise models. Figure 4-9 compares the R-squared value as a statistical measure to identify the best fit function in the regression models. The results show that the R-squared value was highest when two linear lines (piecewise) were applied in the regression analysis. In conclusion, the piecewise regression model yields two separate linear functions for each group, i.e. number of persons up to 300, and greater than 300. The regression equations in Table 4-11 can be considered as the final design equations for the workplace.

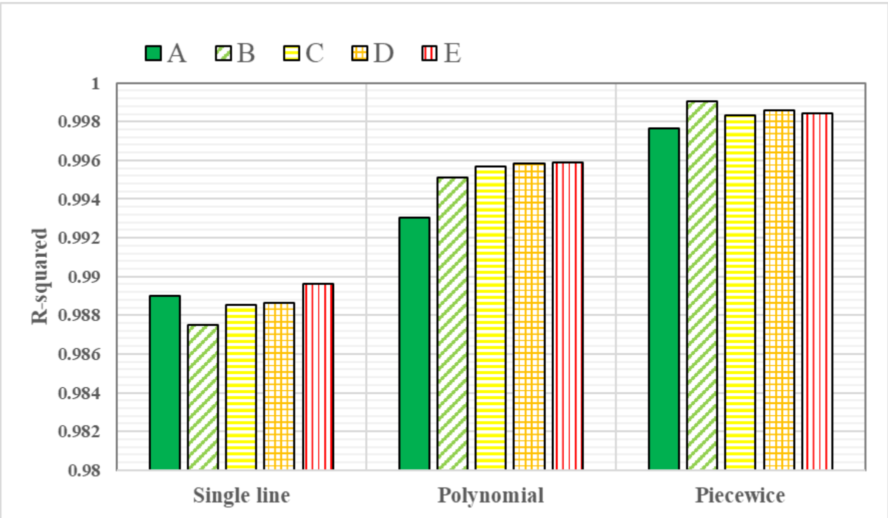


Figure 4-9 Comparison of R^2 values derived from single line, piecewise and polynomial fitting

4.5 Model sensitivity

As discussed in previous sections, the WDEM was developed to simulate demand flow for non-residential buildings and derive new design equations specifically for workplace buildings. Set parameters representative of the workplace have been used as input variables and some assumptions made to support the simulation. These considerations enable the model to derive new design equations for workplaces which can then be used by engineers and designers. However, it is important to understand the sensitivity of the model to any differences in pre-defined settings. The following text discusses the sensitivity of the model to a shift in gender ratio and to changes in *p*-value.

4.5.1 Different gender ratios

One of the assumptions made in calculating appliance provision is that of gender ratio; taken initially to be equal i.e. 50% male and 50% female (50M:50F). As noted in BS 6465, the additional WC provision of 20% is recommended when the gender ratio is not known. It is hence prudent to run the model for different gender ratios to establish the effect on demand flow. For this purpose, two groups of appliances (water efficiency Groups A&B) were tested using different gender ratios. Figure 4-10 shows the flow rates obtained from simulations when the gender ratio was 70M:30F, 30M:70F, and the original 50% male & 50% female. In general, the results show that changing gender ratio does not introduce a significant effect on design flow relative to the benchmark of 50M:50F. Neither change in ratio increased the flowrate, however the greater male ratio can be seen to yield a slightly lower outcome as a result of a reduction in the number of WCs and increased use of urinals. Meanwhile, increasing the female ratio resulted in almost the same flow rate as the equal gender assumption. This is explained by the addition of 20% WCs already added to the appliance provision when the equal gender ratio was considered. This result confirms that the gender ratio generally has no significant impact on demand flow, and, importantly, changing gender ratio will not result in an increased design flow. Thus, the final design equations can be used for any gender ratio in workplace buildings, although should there ever be a case where urinal provision is dominant, then a slight reduction in design flow will help avoid (marginal) oversizing.

It is worth mentioning that it is also possible to calculate appliance provision for the exact number of males and females, then calculate design flow rate. For example, if the number of males and females in a building is known, it is not necessary to run the first part of the

WDEM and the appliance provision can be manually set within the model. Thus, instead of using the design equations, the model can be run to establish a single value of design flow rate based on actual gender ratio for specific cases.

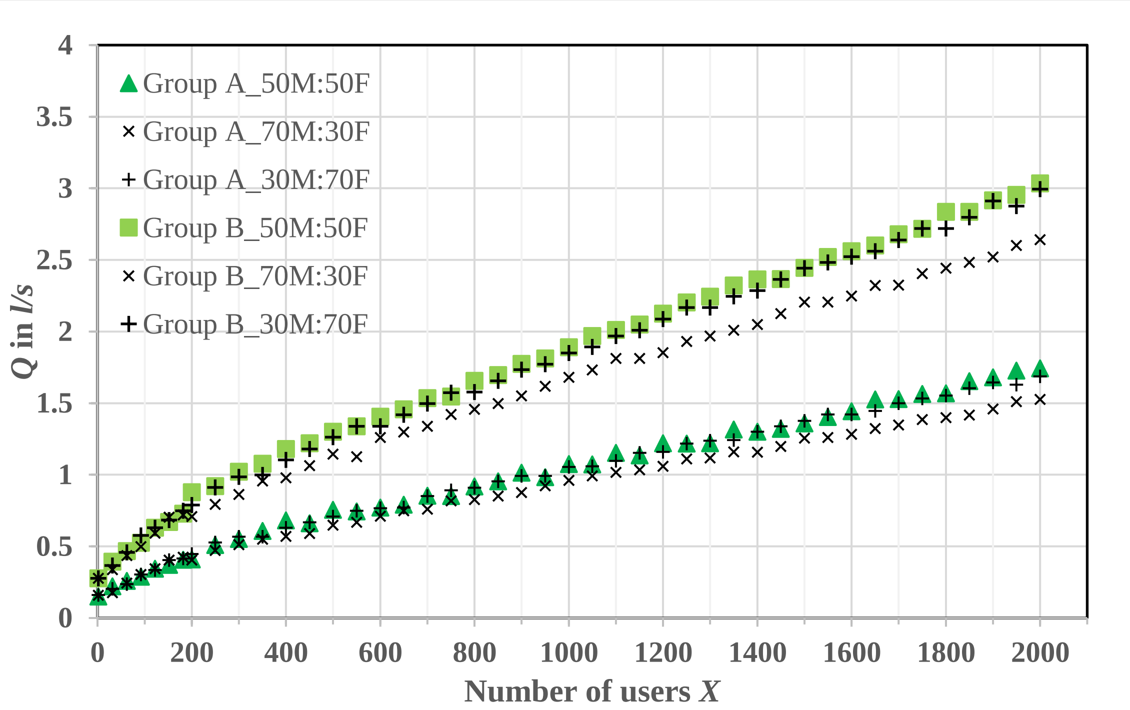


Figure 4-10 Simulated flow rates Q_{99} for different gender ratios for groups A and B

4.5.2 Changing p-values

In cases where there is updated data or improved availability of *p*-value information, this parameter can be updated in the model and new design equations derived. This means it is possible to change these input values without changing the content of the model and hence estimate flow demand for a new set of *p*-values. To assess the sensitivity of *p*-value on the design flow rate in the WDEM, the model was run using different values of *p*: i) increasing p-value by 20% for all appliances, ii) decreasing p-value by 20% for all appliances, and iii) taking into account a specific situation such as COVID 19 when people wash their hands more frequently and use cleaning sinks more than usual, thus increasing *p*-values of hand wash taps by 20% and cleaning sinks by 20%.

The results, Figure 4-11, show that changing *p*-value for all the appliances resulted in changing flow rate values. The change is less notable when the *p*-value of two appliances, i.e. hand wash basin and cleaning sink are increased. The results show that the model is sensitive to this parameter thus emphasising the need for a robust industry reference for *p*-value (currently taken from the CIPHE Guide) or alternatively, for updated data from the sector.

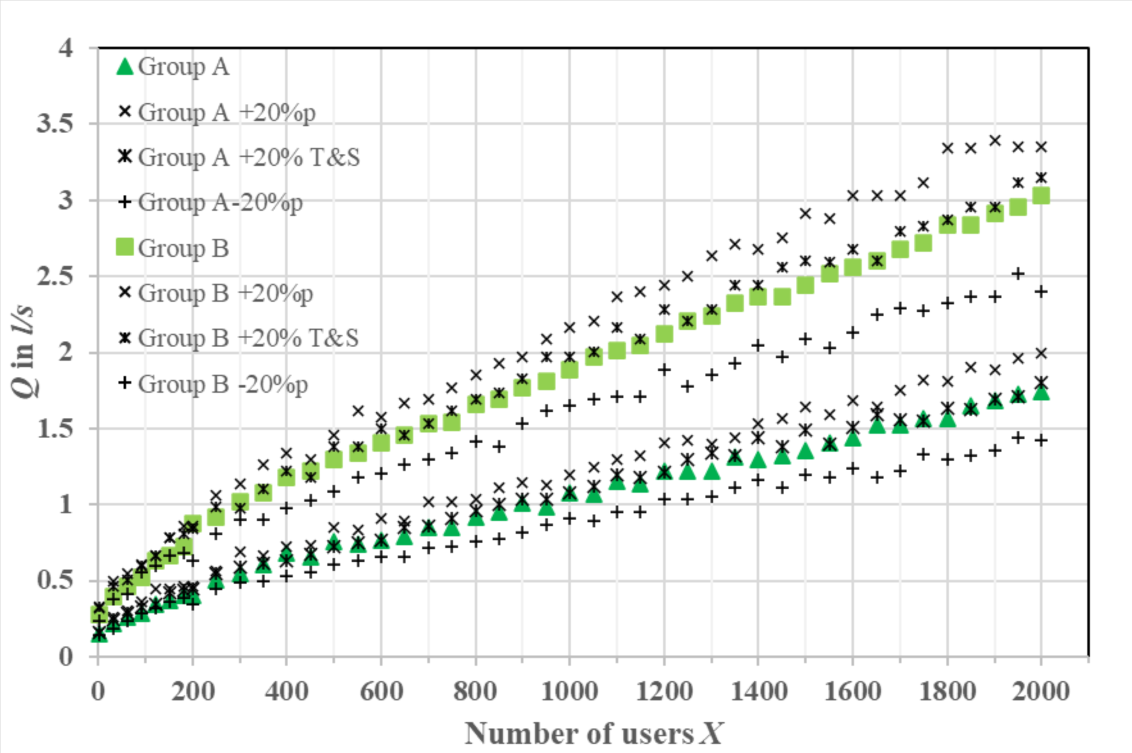


Figure 4-11 Simulated flow rates Q_{99} for different *p*-values for groups A and B

4.5.3 Relationship between the p-value and water-efficient appliances

In this study, new design equations were derived to estimate demand flow for workplace buildings, and for any number of users five values of design flow rate were calculated depending on the water efficiency level of the appliance. It is necessary to explain that the amount of water discharge from the appliances (*q*) was considered in the classification of sanitary appliances depending on efficiency levels. This means that the appliances with low flow rate are classified as water-saving appliances and the level of efficiency decreases with increasing flow rate. For example, taps with a flow rate less than 5 *l/m* are classified as group A. With increasing discharge, the level of efficiency gradually decreases until reaching group E, when discharge is equal to or greater than 15 *l/m*. Thus, the appliance's discharge was the only input variable that changed in the model to estimate demand flow for different groups of sanitary appliances, depending on water saving levels.

Regarding the relationship between *p*-value and water efficient appliance, there is an indirect relationship in terms of duration of using the appliances. As a reminder, *p*-value is the proportion of time that the appliance is in use in relation to the time between successive uses. Some water saving appliances are designed to open for a limited time, such as self-closing taps or sensor taps. Thus, operation time of the appliances may theoretically have an effect on *p*-values. In this study, this factor has not been considered as there is no scientific study to confirm this relationship, and it leads to a relatively smaller value of *p* and consequently less demand flow. However, the general impact of *p*-value on demand flow rate in the model was investigated as discussed in sections 4.5.2.

4.5.4 Cold and hot water consumption consideration

The main aim of this research is to provide a new design approach to estimate total demand flow for buildings as the current design methods result in overestimation. The focus herein is on the main pipe that supplies water to the whole building. Depending on the type of water distribution system in the building, all sanitary appliances (cold and hot) receive water either by gravity from a storage tank or directly from a booster pump set connected to the storage tank. Overestimation of demand flow usually applies in the case of the main pipe before the system distributes through the building and the division into hot and cold pipes. Thus, the design flow rate calculated from this approach can be defined as the total amount of water used by all the end points in the building and including hot and cold water.

The traditional design guides in the UK have taken hot and cold water consumption into account in different ways. For example, the British Standard BS 6700 disregarded the difference in water demand resulting from the use of combined taps and mixers. Thus, the relevant LUs for hot and cold water supplies were added together for each appliance with the exception of the WC, urinal, washing machine and dishwasher, all of which use only cold water. The latest version of the British Standard, BS 8558, explains that care is required when assessing the combined demand of cold and hot water supplies in order to reduce the effect of oversizing. For sanitary appliances fed with both cold and hot water, the traditional loading unit model assumes that the system demand imposed by the appliance is met fully by each separate supply, which is logical when separate cold and hot water taps are fitted to an appliance. BS 8558 states that this assumption is not valid when mixer taps or valves are used and it confirms that individual loading units relevant to the cold and hot water supplies ought not to be added together for sizing any combined cold and hot water demand.

Unlike the traditional design methods that depend on only sanitary appliances to calculate the loading unit and then design flow rate, the WDEM depends mainly on number of users in the buildings to estimate total demand flow and eliminate the problem of cold and hot consumption. The design flow rate obtained from the WDEM thus addresses all water used at all sanitary appliances and includes hot and cold water. In the same way, during flow rate measurement in the case study buildings, the flow meters were installed at the main pipe, either after the storage tanks or booster pumps, to include both hot and cold water.

4.6 Conclusion

This chapter has detailed the development of the WDEM; a new model that provides a better estimation of design flow rate in non-residential buildings, specifically workplaces. The model was programmed in MATLAB to firstly calculate the provision of necessary appliances required for a range of users, followed by a calculation of water demand based on 400,000 Monte Carlo simulation runs. Determining all possible flow rates and the corresponding probability for each water usage event enabled the generation of CDF plots. The 99th percentile was selected as the design flow rate, Q_{99}, thereby allowing a comparison with results obtained from current design guides. This calculation was undertaken for a range of conditions with up to 2,000 users. The model was applied to five groups of sanitary appliances with different efficiency levels. New design equations for estimating flow rate in workplaces have been obtained by establishing best fit functions for the simulated flow rates. In the regression analysis, different models have been applied to the datasets and the piecewise linear model used.

The approach adopted here is novel in that the model incorporates all of the fundamental factors in water demand modelling and utilises users as the main variable in the derivation of design equations. Additionally, it considerations appliance efficiency as a key feature. Selecting a linear relationship for the design equations in the regression analysis not only results in a high value of R-squared (>0.997) but means that those equations will be straightforward for engineers and designers to use. Furthermore, the flexibility and adaptability of the WDEM means it is designed to enable any changes to be made in input parameters and it can be adapted for any change in water usage habits that may happen in the future. This also allows the engineers and designers to estimate design flow rate for any specific situation or building. This is important, in particular, when the change in design flow due to changing *p*-value is taken into consideration. The accuracy of the model and its impact on the oversizing of the water system will be discussed in the following chapters.

Chapter 5 In-situ data collection for case study buildings

5.1 Introduction

Although the WDEM is now able to estimate the design flow rate for workplace settings, it still needs to be tested against real flow data to ensure its performance and accuracy. Recording in-situ flow rate measurements (Q') is a crucial step, not just for validating the developed model, but also to help understand water usage patterns.

This chapter provides details of data collection for three case study buildings, namely the Estates Building, the Postgraduate Centre, and the Hugh Nisbet building at Heriot-Watt University. Prior to commencement of the data collection stage, general information about all three buildings and their usage was investigated to ensure their suitability for this study. Following this, flow rate measurements started with recording all water usage related information. This included general information on the buildings and their usage, sanitary appliances, number of users and flow rate measurements. The flow rate in the main supply pipe within the case study buildings was measured using an ultrasonic flowmeter, thus ensuring the collation of high-quality data. Data was recorded every 5 seconds for a duration of around two weeks for all three case study buildings.

The measured flow data provided the necessary information to understand water usage patterns and identify vital concepts in water demand modelling such as peak hours. The results show similar water usage patterns in the buildings that were considered as workplaces, i.e. the Estates, the Postgraduate Centre and the Hugh Nisbet buildings, with peak hours between 11:00 and 14:00.

Moreover, the data collection activities were extended to include information about sanitary appliances and users in each of the buildings; important elements in water demand modelling, especially when applied as input parameters in the WDEM.

5.2 Selecting buildings and collecting general information

Before starting the data collection, it was essential to have a clear idea about the type and quantity of data required, which buildings should be selected and how to gain access to relevant spaces. As this study focuses solely on non-residential buildings, types of buildings were carefully considered along with building size to cover as wide a range of scales as possible. Invitation letters were sent to introduce the study and clarify the requirements; this included information about the building, users, and measurement duration. Appropriate preparations and provision of all necessary tools were also addressed, including risk assessments, and ethical and health and safety considerations. After liaising with those who manage the buildings and those responsible for running and maintaining the water system, access to the buildings was arranged. In addition to flow rate measurement, the following information was acquired.

5.2.1 Building information

General information about the buildings, including purpose and usage, number of storeys, rooms, washrooms and number of occupants, was recorded. Schematic diagrams and pipe distribution plans helped to clarify the pipe network, including the number and types of sanitary appliances and the location of the storage tank and booster pumps. Using this information, an appropriate location for installation of the flowmeter was selected and both the cold and hot water consumption was monitored. Measurements were taken at the busiest time, taking account of any seasonal variations or any factor that might affect water consumption. All measurements were undertaken between September and December during the normal term-time when most students and staff were using the buildings. The timescale for the measurements was also considered, and a two-week duration selected to capture day/night and weekday/weekend water usage. Depending on the design of the water system, an appropriate part of the network was selected for installation of the flowmeter; at a point suitably distant from bends or fittings.

5.2.2 Number of users

Users can be defined as the primary contributing group in terms of defining water demand for all types of buildings. In residential buildings, groups of users can be categorised based on their age, size, gender and occupation. The number of people per household is of importance because the frequency of use is typically calculated per person. The time of water use is also strongly related to the diurnal patterns of users, such as presence at home and sleep-wake rhythms. Therefore, in residential buildings, the major household types are normally divided into one-person, two-person, and family with children households, while in the case of non-residential buildings, users are defined as a group rather than as individuals. The properties of a user group include mainly diurnal pattern and the number of male and female individuals. Distinction of gender is important as it may affect toilet use, in particular when the washrooms have urinals and toilets. In a specific type of non-residential building such as workplaces, additional information about users may include the number of employees, number of visitors, and working times. Thus, recording the total number of people in the buildings was necessary to support this study. The building occupancy, especially during peak hours, is considered a significant determinant of water consumption in buildings and was hence used as the main variable in the WDEM.

In a small building with one entrance, it may be possible to count the number of people in the building manually. In-Out recording sheets can be prepared to record the number of people entering and leaving the building as well as related times. In one of the case study buildings, the Estates building, the occupancy was recorded by reception staff. The total number of people present in the building each hour was then calculated during the day, i.e. from 7:00 AM to 6:00 PM. In relatively large buildings, manual counting may not be possible and a different method should be undertaken, such as using a people counter or counting the total space. Devices such as the Q-Scan TwinComm, Figure 5-1, can be used to count the number of people in the building. In the Postgraduate Centre, a Q- Scan device was installed, as shown in Figure 5-2, at the main entrance. This device uses a twin beam and bi-directional counter to count people walking in/out of a building. It uses power over ethernet and can be connected to a Virtual Private Network (VPN), or via the internet to a central base computer for multiple sites. This approach is practical for buildings with only one entrance. Otherwise, all the entrances should be controlled or allocated counting devices. Alternatively, in multi-entrance buildings, the number of persons can be obtained from counting the available spaces. For example, counting the number of office rooms in the building and counting how many employees are there, or counting the number of available chairs in a waiting area or restaurant. This approach, which was applied in the Hugh Nisbet Building, required counting the total number of spaces and then monitoring and checking each space. The total number of persons can be calculated by either counting the occupied chairs in quiet times such as the morning, or counting the empty chairs during rush hours such as lunch time. If none of the mentioned approaches are appropriate, numbers of people used to calculate fire escape provision may be applied as a guide.

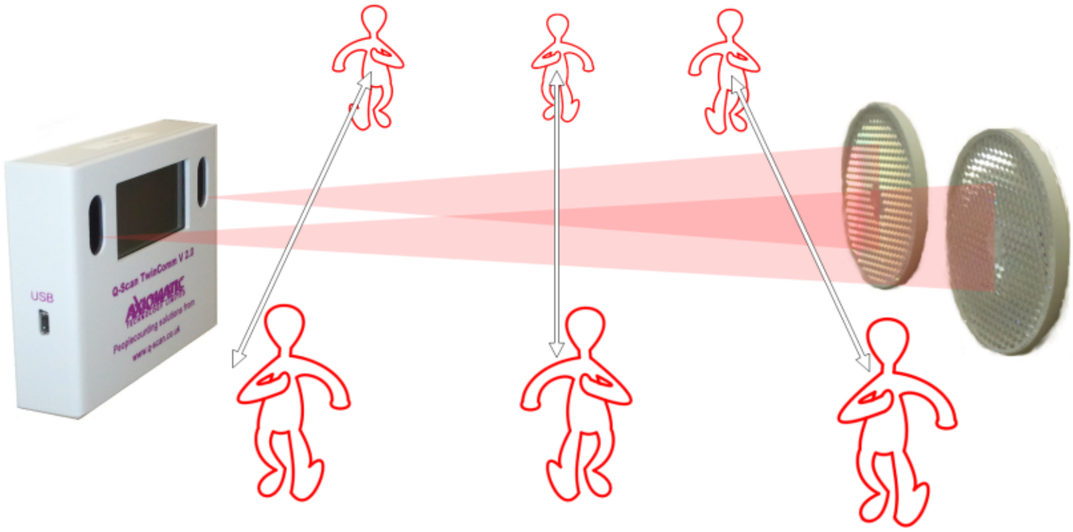


Figure 5-1 People counting device (Q-Scan TwinComm)

Figure 5-2 Q-scan in the Postgraduate Centre

5.2.3 Sanitary appliances

Sanitary appliances can be defined as the points where water is discharged in buildings. In general, there are eleven main types of sanitary appliance: WC, urinal, bidet, hand wash tap, shower, kitchen tap, cleaning tap, clothes washing machine, dish-washing machine, bathtub, and outside tap. Each type of appliance may have various subtypes. Types of appliances are generally associated with the frequency and time of daily use; however, subtypes are mostly linked to duration and intensity (Blokker, 2010)

In the case study buildings, the number and types of all sanitary appliances were recorded along with their flow rates. Floor plans and plumbing drawings were used to count the number of appliances and after visiting the sites, the numbers and types of the appliances were confirmed. For each appliance, in addition to recording its brand name and physical properties, its flow rate was recorded along with operation time if applicable. The information about appliances also included WC and urinal cistern volumes and average operation time to fill the cistern. The flow rate of the taps was measured by fully opening the tap then measuring the amount of time it took to fill a container of pre-defined volume, or by running the tap for a set time and then measuring the volumetric flow. In the case of a lack of space, a flexible bag was used to collect water, and its volume measured using a weight scale or scale container. Thus, the average flow rates for all sanitary appliances were recorded along with the volume and refilling time for the WC and urinal cistern.

The direct flow rate measurement of the appliances permitted an accurate validation of the model, avoiding any assumption or change in flow rate that may have happened due to pressure variation in the system. The appliances in all case study buildings are WC, bidet, urinal, wash hand basin, kitchen sink, cleaning sink and dishwashing machine. Figures (5-3) and (5-4) show examples of the different types of appliances in the case study buildings.

Figure 5-3 Examples of sanitary appliances in the case study buildings

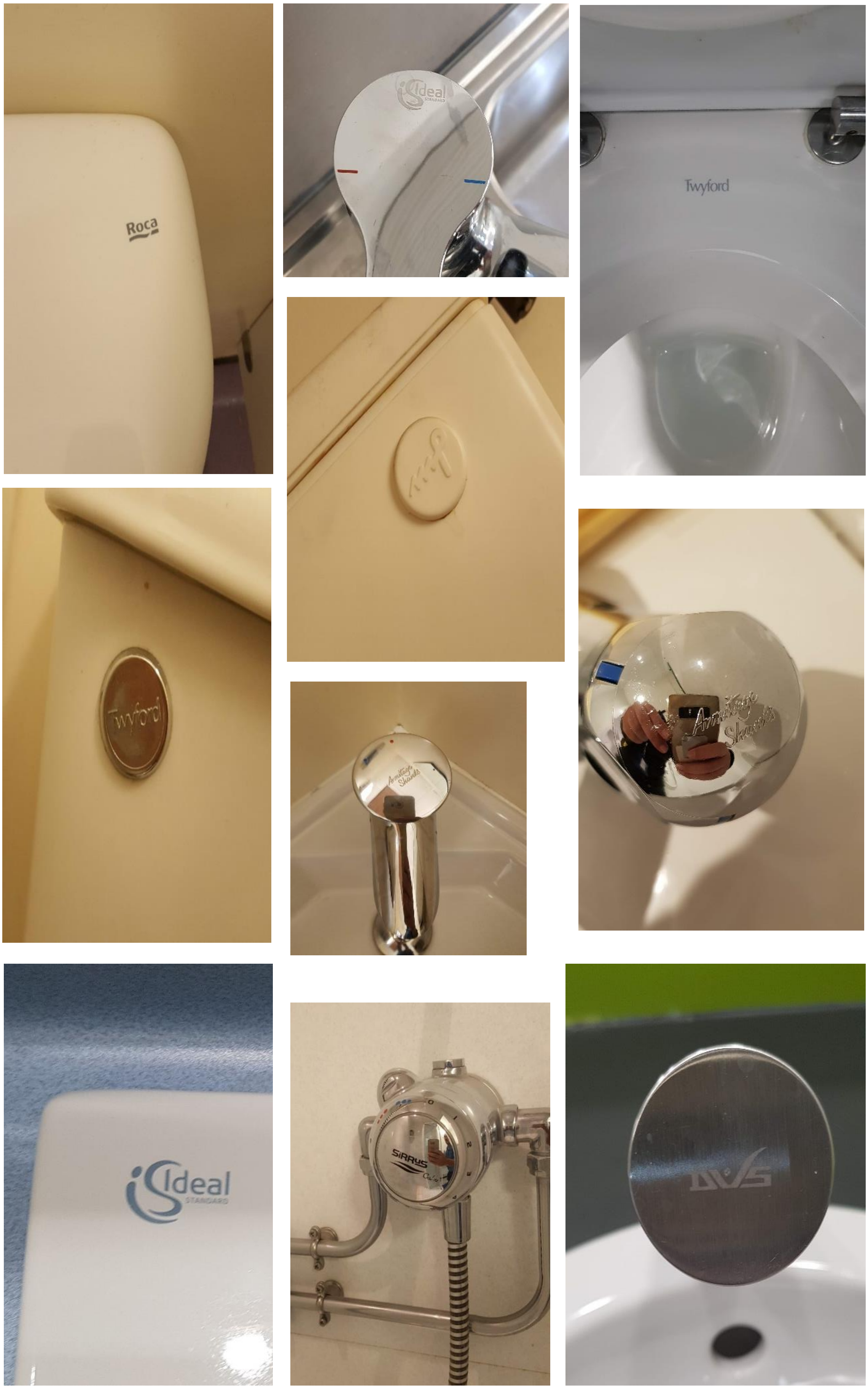


Figure 5-4 Examples of appliance brands in the case study buildings

5.3 Flow rate measurement

In general, there has been very little research into the water demand arising from non-residential buildings. High-quality secondary data for this building type are also very rare. Therefore, direct flow rate measurement was deemed the best option to gather primary data. Despite the accessibility of new technological tools such as ultrasonic flowmeters, direct flow measurement can still be challenging in terms of gaining permission to access buildings and finding enough space to install equipment.

For the purposes of this study, flow data was monitored using a Portaflow 330 (PF330) situated accordingly on the correct part of the pipe network. All necessary actions were addressed to make sure that the measurement work caused no obstruction. The type of data required and the time scale were each set prior to starting the data collection. For example, recording flow rate every 5 seconds helped capture all simultaneous uses of the appliances and enabled the study to make a comparison between measured flow rate on one hand, and design and simulated flow rate on the other. Other parameters, such as volume per day and the number of pulses per day at different temporal and spatial scales, can be calculated from the original flow data. This information is helpful for gaining a better understanding of water usage patterns. Regarding the determination of duration of measurement, the functionality and usage of the buildings were considered. In residential buildings, seven days' measurement is usually preferable to cover both weekdays and the weekend, while in non-residential buildings, the focus should be on working hours during weekdays as most workplace buildings are out of use during the night and at weekends. However, the capacity of the flowmeters was sufficient for collection of flow rate data for 12 days, including the whole week and following five working days (for each case study building).

The process of data collection dates back to 2018 when the initial purpose was to assess how to use the flowmeters and check their accuracy. The initial flow rate data were also used to confirm that the current design codes result in overestimation of demand flow in non-residential buildings. After developing the WDEM, all necessary requirements were undertaken to gather high quality data on flow rate, users and sanitary appliances. Flow rate measurement was then started in the case study buildings in August 2019. Flow rate measurement was undertaken during the first semester of the academic year, which meant this could be observed during the busiest time when the buildings were almost fully occupied. It is important to note that all the data collection was undertaken before the

COVID 19 pandemic, i.e. before the announcement of the national lockdown in the UK in late March 2020. Thus, the data used in this study were collected during a normal working period. The flow rate data herein, therefore, represent a normal situation outside COVID 19. This can be considered a positive factor of this study in terms of design flow estimation as the flow rate was measured when the buildings were being used normally. This means flow rate was measured without any impact of COVID 19 restrictions on water usage, such as decreased number of occupants in the buildings because of working from home or because of illness.

Before starting the work, all flowmeters and devices were inspected to make sure they are safe. All devices were PAT (Portable Appliance Testing) tested by technicians and marked ‘passed’, Figure 5-5. Another important task was the determination of appropriate locations to install the flowmeters or to measure cistern capacity, especially since the removal of wall panels was required in some cases, Figure 5-6. The details of measurements, flowmeter and requirements are given in the following sections.

Figure 5-5 PAT certificate example

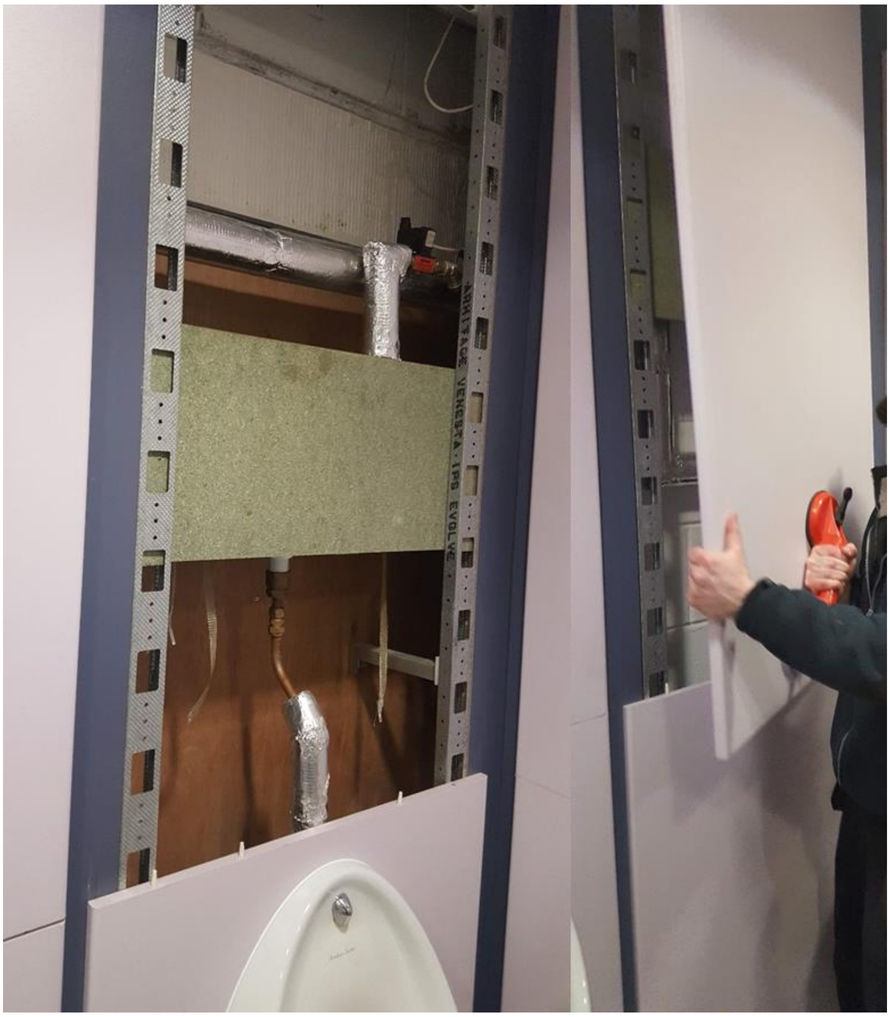


Figure 5-6 Removal of a wall panel by a plumber

5.3.1 Flow measurement device (PF 330)

Whereas many studies have focused on measuring the amount of water consumption per day, this study focusses on the instantaneous demand flow in a building, where the time between measurements under consideration may be taken to be of the order of 5 seconds. To support this study, Heriot-Watt University was able to provide a number of Portaflow 330 flowmeters, Figure 5-7. This flowmeter is designed to work with clamp-on transducers to enable measurement of the flow of a liquid within a closed pipe without the need for any mechanical parts to be inserted through the pipe wall or protrude into the flow. The Portaflow PF330 is an ultrasonic flowmeter with the ability to accurately measure the flow rate of any fluid within any kind and size of closed pipe, using ultrasonic transit time. It is controlled by a microprocessor system which includes a wide range of data that enables the device to be used with pipes made of almost any material and with a diameter ranging from 13mm up to 5000 mm, with a range of fluid temperatures. The main characteristics of the Portaflow 330 (Version 2.07.007, Serial No. 11975) are:

- 98k stored data points
- Continuous signal monitoring
- RS232 output
- USB output
- Pulse output (volumetric or frequency)
- 4-20mA, 0-20mA or 0-16mA output

Figure 5-7 PF330 Flowmeters provided by Heriot-Watt University

The PF330 consists of different components, as shown in Figure 5-8, which can be classified into two main parts; the first, the Portaflow 330. The second part comprises components to be installed on the pipe, including a set of guide rails, ruled separation bar, transducer set, ultrasonic couplant (a liquid that facilitates the transmission of ultrasonic energy from the transducer into the pipes), test block and two lengths of chain.

The flowmeter can measure and display the instantaneous fluid flow rate, velocity and totalised values, with the readings saved in the data logger. Volumetric flow rates and total volumes can also be displayed on the screen, Figure 5-9.

Figure 5-8 Portaflow PF330 components

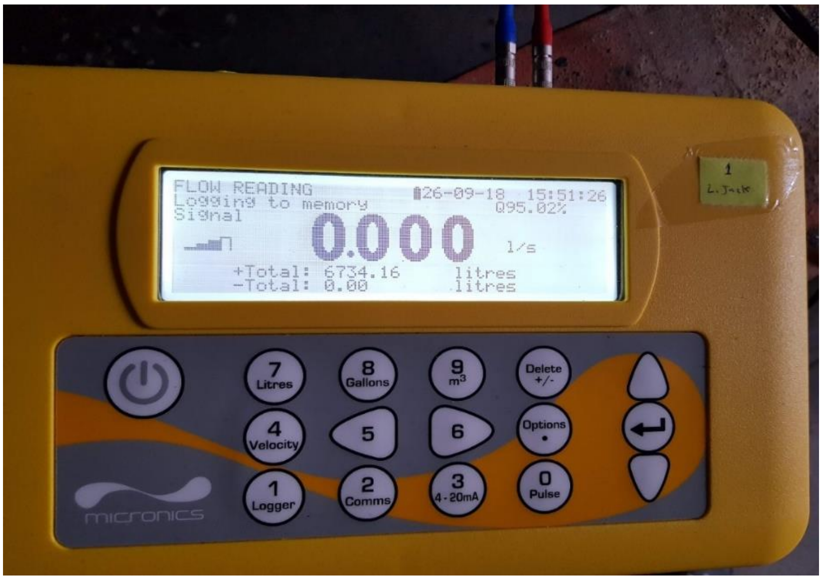


Figure 5-9 LCD display of Portaflow 330

5.3.2 Accuracy of Portaflow 330

The quality of data collection is important as these will be used not only for validation of the WDEM model but will also be used for understanding water usage patterns in non-residential buildings. High-quality data also helps future researchers make the right decisions about further studies in this area. In this study, the newest version of the non-intrusive flowmeter has been used to measure flow rate. Before starting the data collection, the flow meters were tested to ensure their performance and accuracy. According to the manufacturer's specification (Micronics, 2020), the accuracy of the flowmeter is as follows:

- (±0.5% to ±2%) of flow reading for flow rate >0.2 m/s and pipe diameter >75mm
- (±3%) of flow reading for flow rate >0.2 m/s and pipe diameter in range 13-75mm
- (±6%) of flow reading for flow rate <0.2 m/s.

Because the size of the case study buildings ranged from small to medium scale, the pipe sizes were no greater than 75 mm, and the accuracy of the flowmeters therefore assumed to be ±3%. As a double-check and to make sure the device's accuracy was not below the above range, all flowmeters were first tested in the laboratory by comparing their readings with manually measured water flow. For this purpose, the flowmeters were installed on a 15 mm copper pipe which fed a sink tap to measure flow rate. This test was repeated several times for each flowmeter to record the average reading of the flowmeters. At the same time the flow rate was calculated manually by measuring the volume of water and the time. The accuracy of the flowmeters was checked by comparing the reading with measured flow rate and calculating the percentage error. The average error of the flowmeters was found to be, 1.8%, which is less than that given in the manufacturer's manual (±3%). This confirmed that the flowmeters would work properly with an acceptable level of error.

Regarding larger scale buildings, the flowmeters' accuracy was checked by comparing readings with a fixed water meter. For this purpose, the Postgraduate Centre at Heriot-Watt University was selected; this is a relatively new building that has a smart metering system, Figure 5-10, to monitor water usage in the building. Water and energy data for this building are available online and can be accessed through the university link. However, this water meter is not as accurate as the flowmeter, and it can only measure the amount of used water every half hour, whereas the Portaflow PF330 can measure the amount of used water every 5 seconds. The flowmeters were installed on the same main pipe to which the water meter was fixed to measure water flow for a duration of around 12 hours. The data from the flowmeters were compared to the water meter readings. An example of the results is shown in Figure 5-11. This clearly presents an excellent agreement of flow rate, volume and water usage patterns for the flowmeters (grey and black) and the fixed water meter (dotted pattern). The slight difference in water meter reading can be traced back to the conversion of flow rate units because the flow rate data obtained from the flow meters were in *l/s* with three decimal digits, while the fixed water meter measured water flow in *m^3/30 minutes* with only one decimal digit. The results from both the laboratory test and fixed water meter established the accuracy of the Portaflow 330 and confirmed that the flowmeters could be used to gather high-quality flow rate data for the purpose of this research.

Figure 5-10 The fixed water meter in the Postgraduate Centre

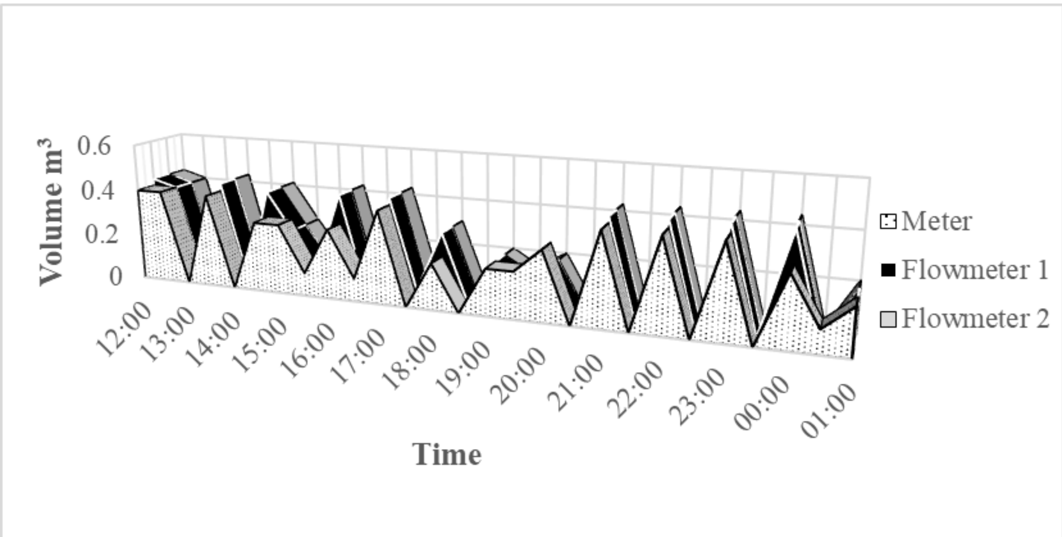


Figure 5-11 Comparison between flow rate readings obtained from the flowmeters and the water meter in the Postgraduate Centre

5.3.3 Technical requirements

Careful entry of information into the flowmeters is required in order for them to read the flow rate data accurately. The relevant information about the pipe and the fluid should be entered before starting measurement. This information includes pipe diameter, wall thickness, material, type of fluid and temperature, all of which have a direct effect on the accuracy of the measurement. During installation, all insulation was removed, Figure 5-12. A digital vernier caliper, Figure 5-13, was used to measure the external diameter of the pipe and then the interior diameter and pipe thickness were obtained from the manufacturer’s manual or standards. Table 5-1 presents an example of a pipe table used to obtain copper pipe properties, other pipe tables are available in Appendix A. Water temperature also needed to be checked. A specific temperature scale was fixed on the pipes to record temperature and find the average water temperature as shown in Figure 5-14.

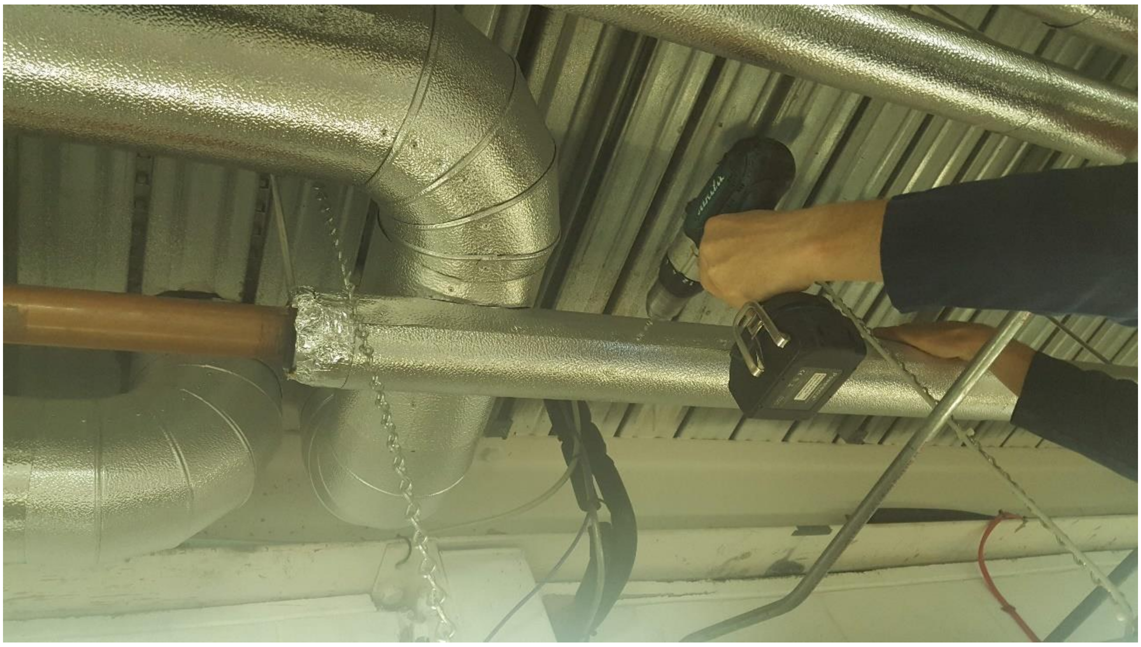


Figure 5-12 Removing insulation material around the pipe

Figure 5-13 Digital vernier caliper for measuring pipe diameter

Figure 5-14 Temperature scale for measuring water temperature

Table 5-1 Copper pipe properties (British Standard 2871)

(mm)	Outside Diameter (mm)	Table X Half hard light gauge tube		Table Y Half hard an annealed tube		Table Z Hard drawn thin wall tube	
		Thickness (mm)	Maximum Working Pressure (N/mm^2)	Thickness (mm)	Maximum Working Pressure (N/mm^2)	Thickness (mm)	Maximum Working Pressure (N/mm^2)
6	6	0.6	13.3	0.8	14.4	0.5	11.3
8	8	0.6	9.7	0.8	10.5	0.5	9.8
10	10	0.6	7.7	0.8	8.2	0.5	7.8
12	12	0.6	6.3	0.8	6.7	0.5	6.4
15	15	0.7	5.8	1	6.7	0.5	5
18	18	0.8	5.6	1	5.5	0.6	5
22	22	0.9	5.1	1.2	5.7	0.6	4.1
28	28	0.9	4	1.2	4.2	0.6	3.2

5.3.4 Installation of Portaflow 330

Before using the flowmeters, all were tested and prepared in the laboratory. After ensuring that the selected location satisfied the distance requirements, the pipes were prepared by removing any dirty or loose material to obtain a clean and smooth surface. Good contact was aided by the application of a couplant between the transducers and the pipe surface to help achieve a strong ultrasound signal and correspondingly, high quality flow data, Figure 5-15. A steel scaled bar was used to set the distance between the transducers depending on the value calculated automatically by the flowmeter itself. Finally, the transducers were connected to the flowmeter using coaxial cables.

Meanwhile, the flowmeters were configured by selecting the time scale and flow rate units and entering information on the pipe and the fluid, such as the pipe's external diameter, the thickness and material of the pipe, lining material and thickness, and fluid type and temperature. Data can be stored in the flowmeter's internal memory and can be directly transferred to a computer or printer through a USB or RS232 interface or saved for downloading at a later date (Micronics, 2020).

Figure 5-15 Guide rail and transducers installation

5.3.5 Transferring the data

The Portaflow 330 has an internal memory which is able to save about 200,000 datapoints. The capacity of the device therefore depends on the number of readings, which varies with the time between two measurements. A longer time between two measurements reduces the number of readings and vice versa. For example, the number of readings for a weeks' measurement on a 5 second time interval would be more than 120,000 pulses, while, for a 10 second time interval this would be only 60,000. Thus, increasing the time between two measurements enables the device to save more data and take measurements for longer. The saved data can be transferred to a PC or laptop during operation or later via the connection cable. If the flowmeter is left to save a large data set, it may not be easy to manage and transfer. In general, there are two ways for transferring the data from the flowmeter to a computer; these were:

- Portagraph III (which is provided with the Portaflow 330 device)
- Hyper Terminal (which came with the Windows operating systems)

Figure 5-16 is an example of flow rate data after transfer to a computer using the Portagraph III. This software helps to plot the data and present water flow patterns without the need for other programs such as Excel or MATLAB.

As water demand is an inherently variable process and any metered consumption data may include a measure of variability and uncertainty, a simple filter may need to be applied to the data in order to ensure the integrity of the flow rate measurement. For example, any unexpected reading or extremely high water use that casts doubt on the accuracy of the measurements should be excluded from the data. Thus, flow rate data for all case study buildings were saved in an Excel sheet to be analysed.

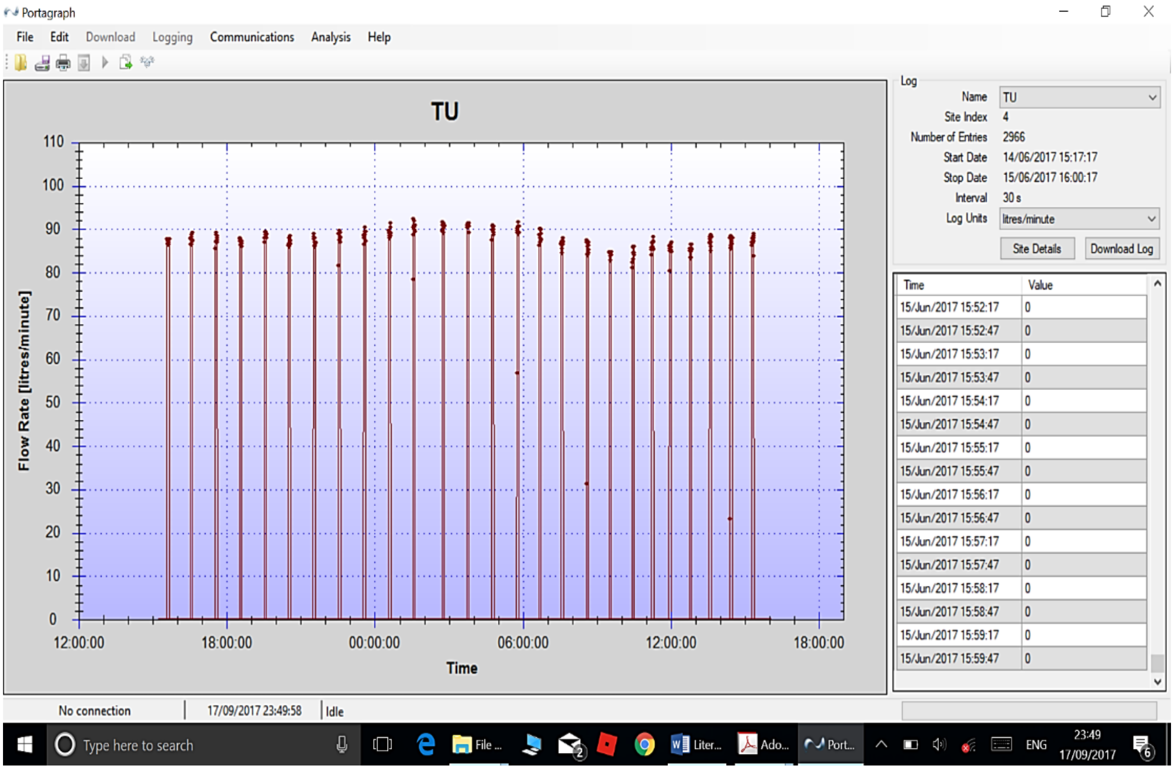


Figure 5-16 Flow rate data using Portagraph III software

5.4 Case study buildings

Another essential part of the data collection process was to identify appropriate buildings to carry out the flow measurement. Initial investigation and site visits beforehand helped to make a correct selection of buildings. As this research focuses on non-residential settings, most of the buildings inside Heriot-Watt University's Edinburgh campus were appropriate for this purpose and more than seven buildings were preselected to be used as case studies. Following further investigation and consideration of the building types and sizes, this was reduced to a more manageable number and three buildings were finally selected.

The selected case study buildings all have different water supply systems. However, all of them have large storage tanks located within the roof space or plant room that receive water from the mains pipe, fed to the building either by gravity or using a booster pump set. As shown in Figure 5-17, the flowmeter was installed on the main water supply pipe between the storage tank and the booster pumps in the plant room, or on the outlet pipe of the storage tanks in gravity-fed buildings. Installing the flowmeters on the main pipes enabled them to record the total flow rate for both cold and hot water usage. The flow rate was recorded every 5 seconds for a duration of around two weeks. The floor plan and pipe schematic for the case study buildings are shown in Appendix B, while the description and core information for each building is given in the following sections.

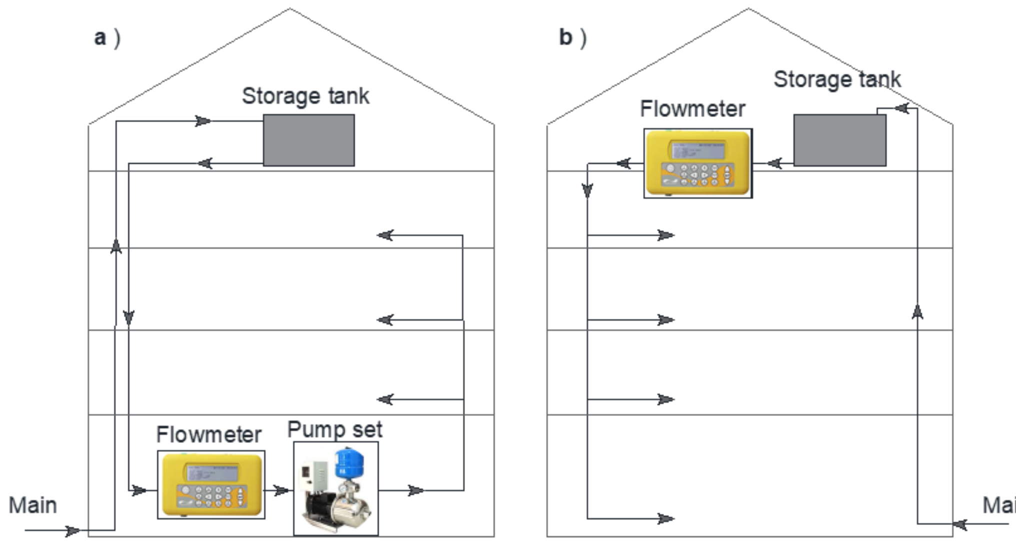


Figure 5-17 Schematic illustration of water system and flowmeter location in the case of a) booster pump, b) gravity fed

5.4.1 Estates building

The Estates building is a two-storey office building, Figure 5-18, used by staff and visitors. The building can be defined as a small-scale office building and was used by a maximum of about 50 persons during flow measurement. The number of persons in the building was recorded by reception staff. The building is supplied with water by gravity from a storage tank located in the roof. The flowmeter was installed on the outlet pipe of the storage tank, Figure 5-19.

Figure 5-18 Estates building

Figure 5-19 Installation of PF 330 in Estates building

The flow rate was monitored for 12 days from Monday 28th August until Friday 8th September 2019. The maximum flow rate Q'_{max} was 0.69 *l/s*, which was recorded on Monday 4th September between 10:00 and 11:00. The average flow rate Q'_{avg} was 0.17 *l/s*, and the 99th percentile $Q'_{0.99}$ was 0.42 *l/s*. Figure 5-20 shows the 12 days' flow rate measurements, peak day and peak hour for the building. The figure illustrates the regular water demand pattern for all measurement periods which best matches the diurnal pattern in non-residential buildings. It is also clear that the majority of water usage happened during normal work hours and there was no water usage during the night. It also shows regular water usage during weekdays and limited usage during weekends. The dashed-line in the Figure represents the 99th percentile ($Q'_{0.99}$) which is considered design flow rate. To obtain the $Q'_{0.99}$, the flow rate data were analysed to determine normal and cumulative distribution function and generate the full CDF of measured flow rate. Then, the 99th percentile flow rate $Q'_{0.99}$ was extracted from the CDF as shown in Figure 5-21.

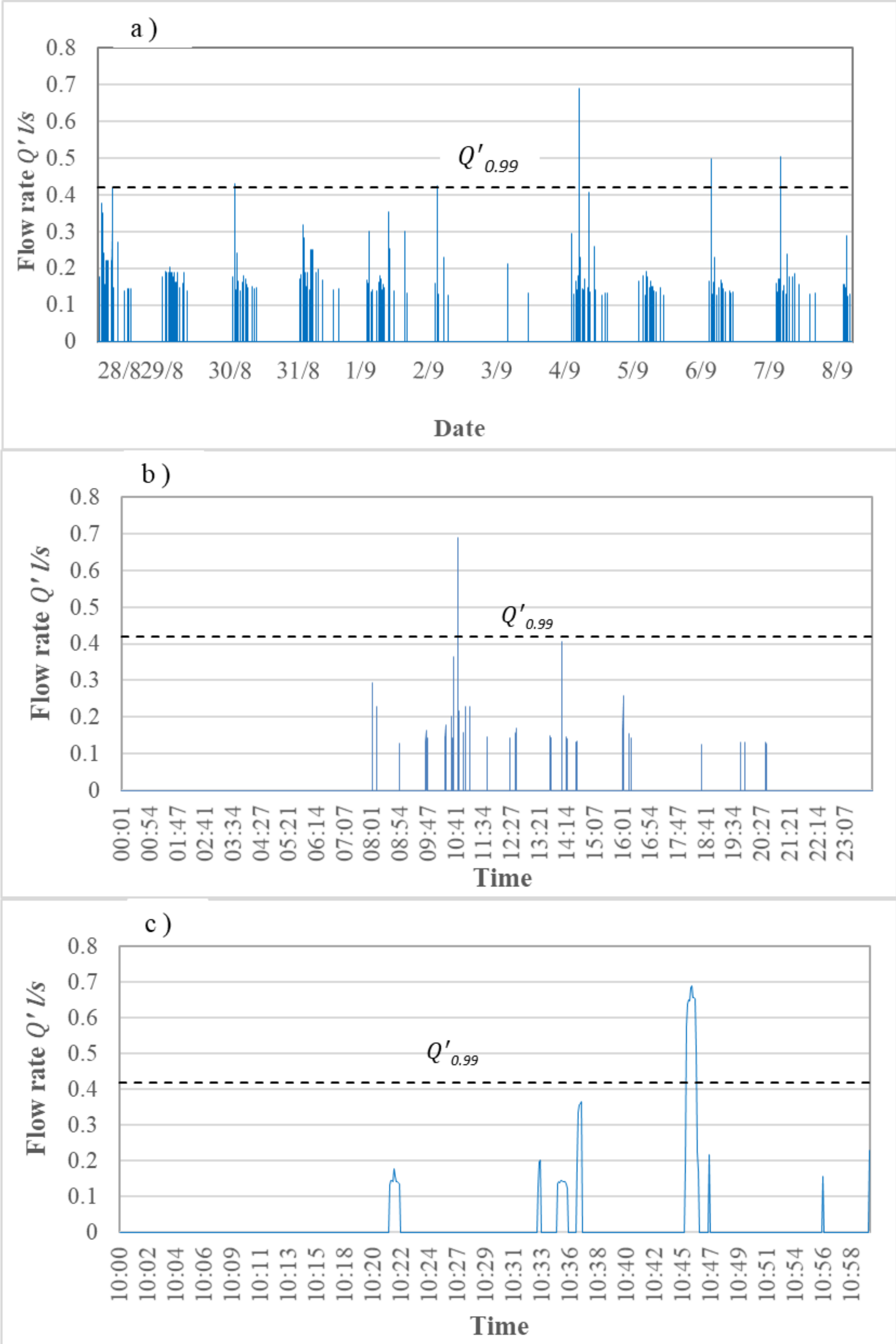


Figure 5-20 Measured flow rate in the Estates building: a) 12 days, b) peak day, and c) peak hour

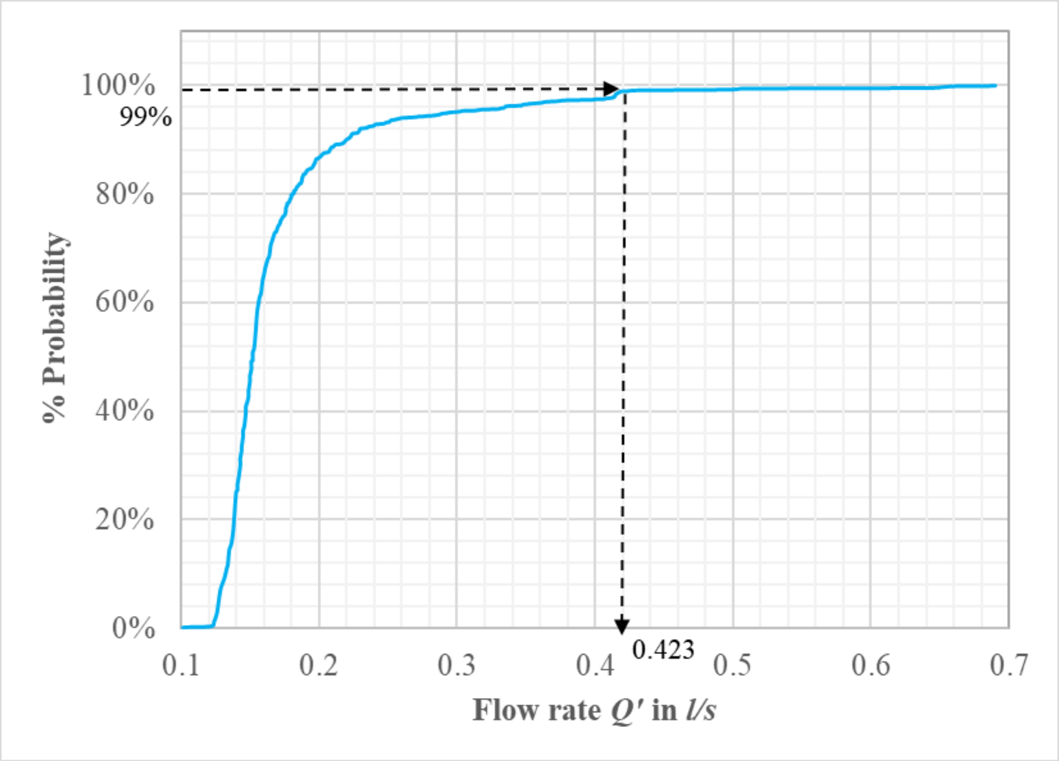


Figure 5-21 CDF of measured flow rate and value of the 99th percentile for the Estates building

5.4.2 Postgraduate Centre

The Postgraduate Centre, Figure 5-22, is a mixed-use building with an existing smart metering system used to measure water and energy consumption. It is a three-storey building consisting of offices, a 150-seat lecture theatre, two additional lecture rooms, study and social areas, self-catering facilities, and a coffee shop for staff and students. The Postgraduate Centre is a relatively new building and is provided with water-efficient appliances such as self-closing taps and sensor urinals, Figure 5-23. During flow measurement, the building was used by a maximum of about 450 persons as recorded by a Q-scan device. Water is fed from a storage tank to the plant room in the basement, Figure 5-24, and is then delivered to the entire building by a set of booster pumps. The flowmeter was installed on the outlet pipe of the storage tank before the booster pump in the plant room to measure both cold and hot water flow, Figure 5-25.

Figure 5-22 Postgraduate Centre

Figure 5-23 Self-closing water tap in the Postgraduate Centre

Figure 5-24 The plant room in the Postgraduate Centre

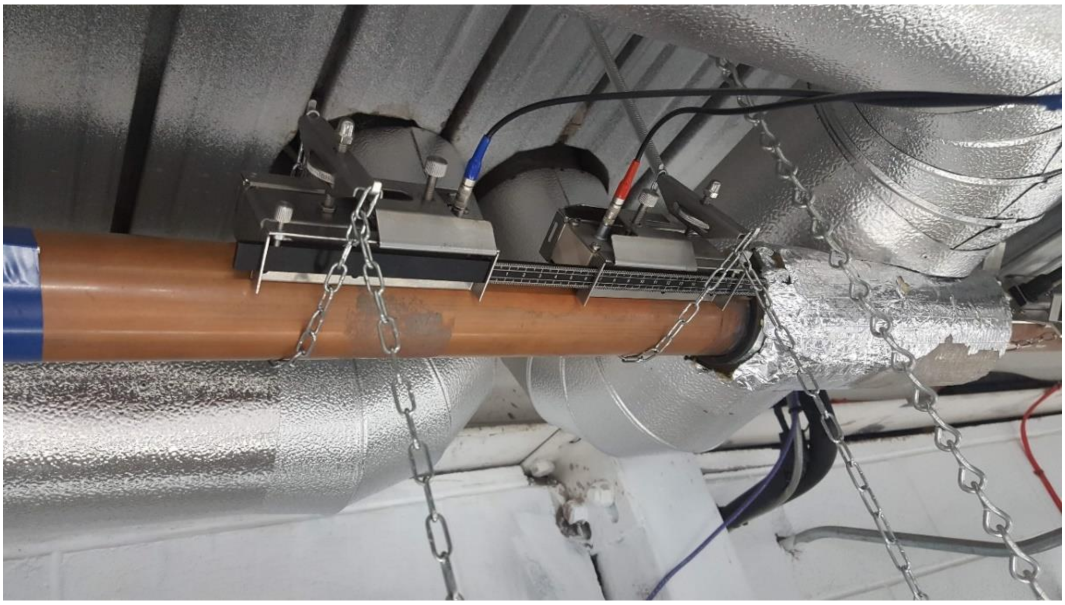


Figure 5-25 Installation of PF330 in the Postgraduate Centre

The flow rate was monitored for 12 days from Monday 4th September until Friday 15th September 2019. The maximum flow rate Q'_{max} was 0.98 *l/s*, which was recorded on Thursday 14th September between 12:00 and 13:00. The presence of a cafeteria in the building meant that the busiest time was during lunch. The average flow rate Q'_{avg} was 0.31 *l/s*, and the 99th percentile $Q'_{0.99}$ was 0.62 *l*/s. Figure 5-26 shows the twelve days' flow rate measurements, peak day and peak hour for the building. The figure illustrates the regular water demand pattern for all measurement periods which best matches the diurnal pattern in non-residential buildings. After generating the full CDF for the flow data, the $Q'_{0.99}$ 'design' rate was determined, Figure 5-27. Unusual usage can be seen during the night and weekend in this building. This issue was discussed with engineers and technicians, and after site investigation it was attributed to leaks through sanitary appliances which are mostly automatic or have sensors to control operation. For example, each set (2-3) of urinals in a toilet was controlled by a sensor installed in the ceiling, with a faulty sensor causing regular discharge of the urinals. This issue may affect the total amount of water consumption in the building, especially during the night when there are no water use activities, but it has less effect on maximum flow demand because use of most of the appliances is usually highest during peak hours.

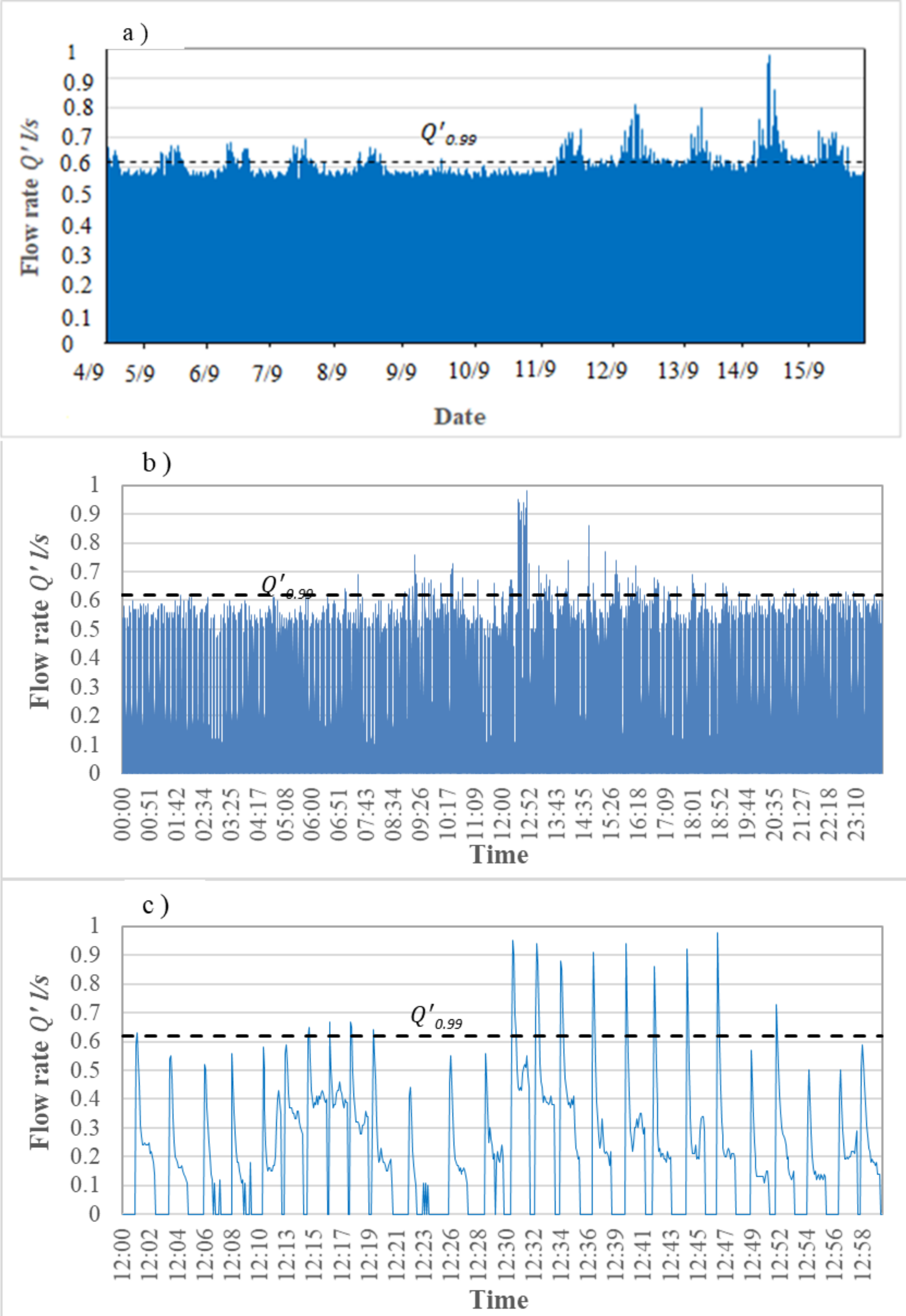


Figure 5-26 Measured flow rate in the Postgraduate Centre: a) 12 days, b) peak day, and c) peak hour

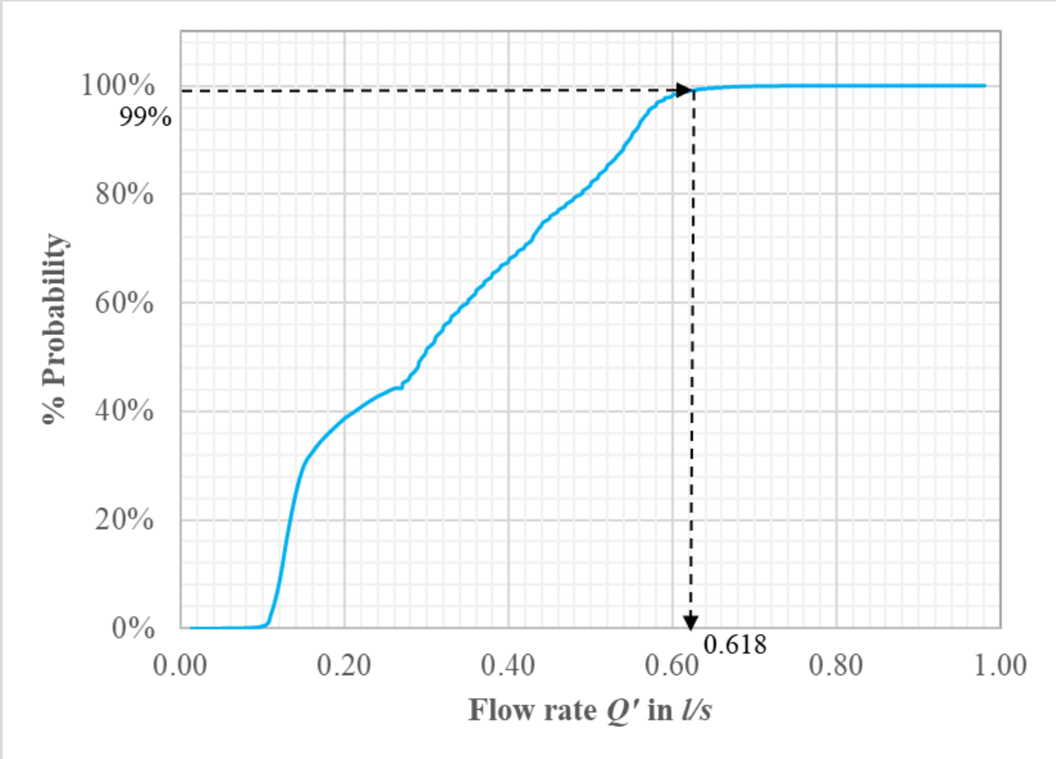


Figure 5-27 CDF of measured flow rate and value of the 99th percentile for the Postgraduate Centre

5.4.3 Hugh Nisbet Building

The Hugh Nisbet Building is a three-storey mixed-use building, Figure 5-28. The building includes offices, a shopping area, canteen and coffee shop. It is a mixed-used building with two main entrances and four secondary entrances. The existence of more than one canteen and coffee shop with multi entrances made collecting data about number of users difficult. The building was being used by about 1,200 persons when the measurement was undertaken. It is worth mentioning that the building is provided with water-efficient appliances including sensor mixers, Figure 5-29, and sensor urinals, Figure 5-30. Water is distributed to the building from two storage tanks which are located on the roof. One feeds the whole building with hot water and part of the building with cold water. The other tank feeds part of the building with cold water only. Because of the complexity of the network and presence of two storage tanks, it was not possible to record total flow rate using just one flowmeter. Two flowmeters were hence used to measure flow rate from the two tanks, Figure 5-31. The two flowmeters were set up for the same building to record flow rate at exactly the same time, and then the sum of both readings was taken as total flow rate for the entire building.

Figure 5-28 Hugh Nisbet Building

Figure 5-29 Sensor water taps in Hugh Nisbet Building

Figure 5-30 Sensor urinals in Hugh Nisbet Building

Figure 5-31 Installation of PF330 in Hugh Nisbet Building

The flow rate was monitored for 12 days from Monday 18th September until Friday 29th September 2019. The maximum flow rate Q'_{max} was 1.62 *l/s*, which was recorded on Tuesday 25th September between 12:00 and 13:00. The average flow rate Q'_{avg} was 0.37 *l/s* and the 99th percentile $Q'_{0.99}$ was 1.111 *l/s*. Figure 5-32 shows the 12 days' flow rate measurements, peak day and peak hour for the building. Similar to the Postgraduate Centre and Estates building, the figure shows the regular water consumption during normal work hours for all measurement periods with less water usage during the weekend and no water consumption during the night. Figure 5-33 shows the full CDF of observed flow rare and the extraction of $Q'_{0.99}$ to be used in the analysis.

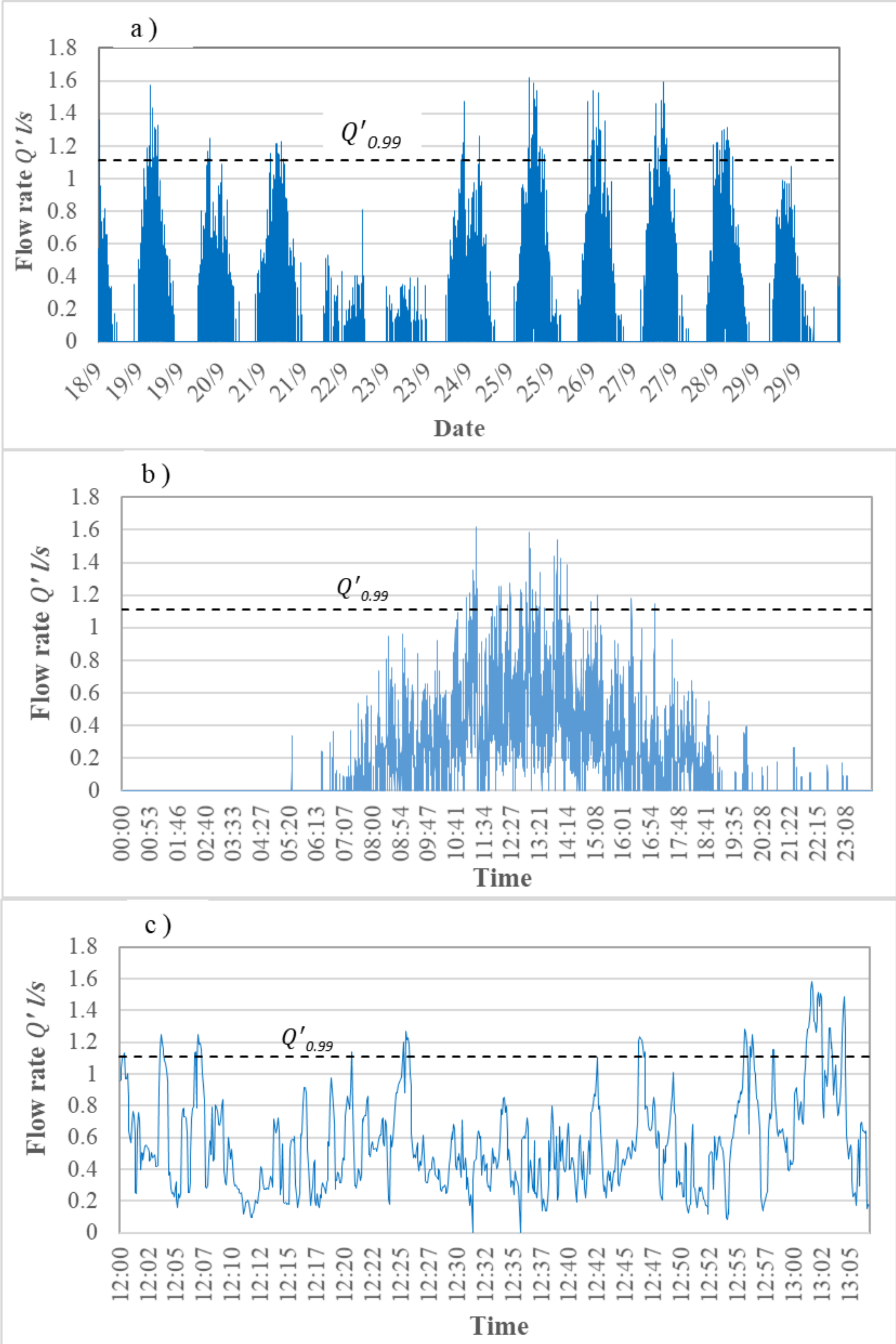


Figure 5-32 Measured flow rate in the Hugh Nisbet Building: a) 12 days, b) peak day, and c) peak hour

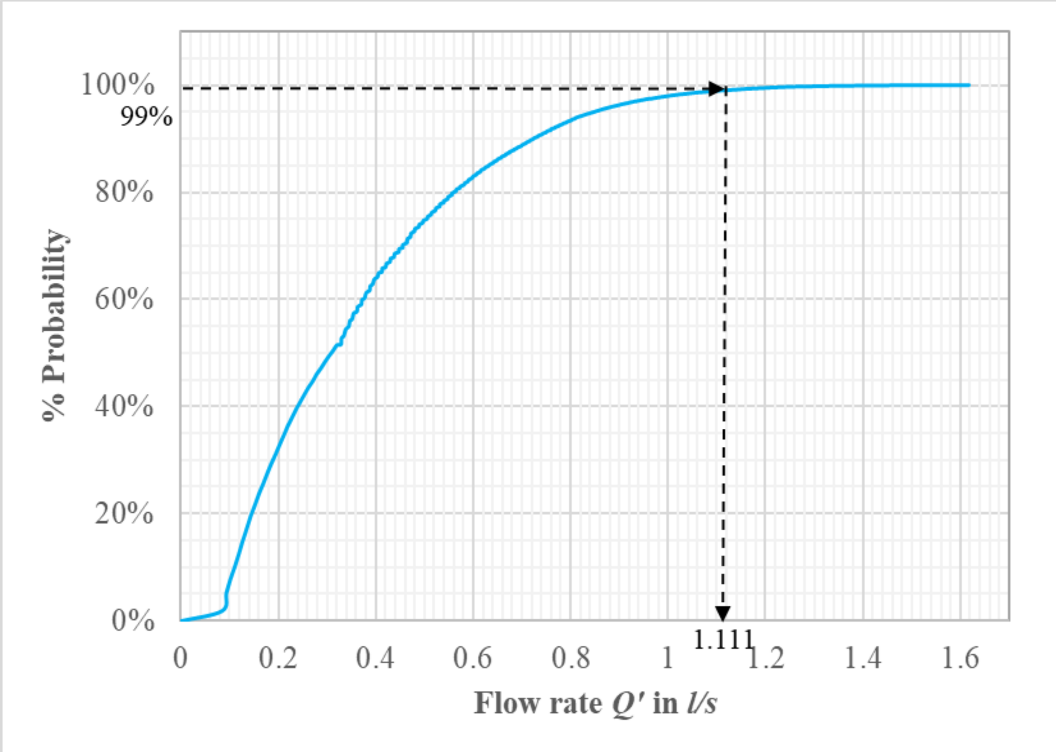


Figure 5-33 CDF of measured flow rate and value of the 99th percentile for the Hugh Nisbet Building

5.5 Results and discussion

5.5.1 Average, 99th percentile and maximum flow rates

After recording the water demand in the case study buildings, the data was analysed to generate the respective Cumulative Distribution Functions (CDFs). These were used to determine flow rate values for any level of reliability, including the 99th percentile. As noted previously, most design guides, including the British Standards, use a 99th percentile level of confidence to determine the design flow rate since a 1% failure is deemed generally acceptable. The 99th percentile flow rate ($Q'_{0.99}$) was hence extracted from each CDF in order to present the flow rate for which the system should be designed. This value will be used to validate the WDEM and in comparisons with design and simulated flow rate. In addition, the average flow rate Q'_{avg} was calculated for comparison. The results of the flow measurements are summarised in Figure 5-34; here, the values of Q'_{max} , $Q'_{0.99}$ and Q'_{avg} are presented.

The results show that accepting a 1% failure rate yields a considerable reduction on flow rates. However, while some studies consider the 99th percentile as a high level of confidence and a reason for overestimation of demand flow, in this stage of the study this level is considered acceptable, especially since it has been adopted in all British standards. To obtain a bigger picture of demand flow, the values of Q'_{max} , $Q'_{0.99}$ and Q'_{avg} were plotted based on the number of users in the buildings with the best fit line, as shown in Figure 5-35.

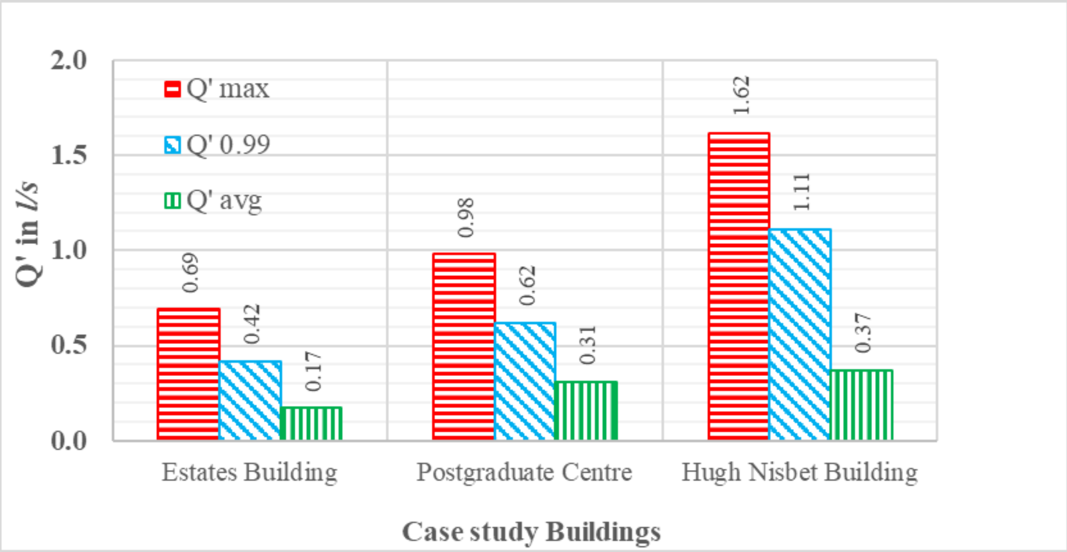


Figure 5-34 The values of Q'_{max} , $Q'_{0.99}$ and Q'_{avg} for all case study buildings

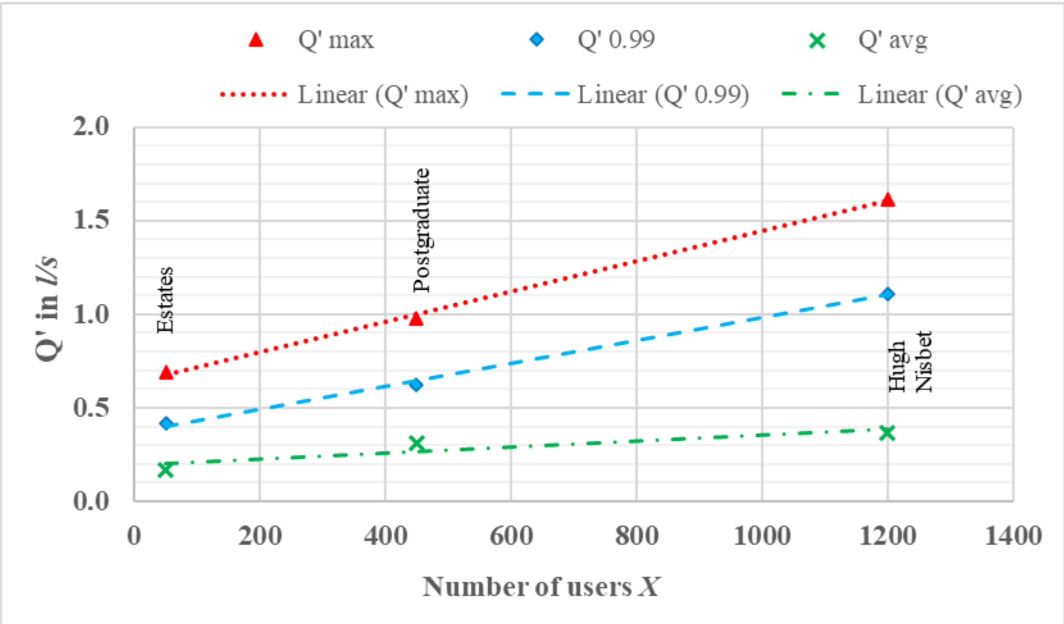


Figure 5-35 The values of Q'_{max} , $Q'_{0.99}$ and Q'_{avg} with the trendlines for all case study buildings

5.5.2 Water usage patterns

Understanding water usage patterns is essential in water demand estimation studies. It can be seen from Figures 5-20, 5-26 & 5-32 that water usage is significantly less during the weekend compared to weekdays and there is less or no water usage during the night in all buildings. To better understand the water usage patterns in the case study buildings, the data was analysed to calculate the frequency of water usage in terms of number of water events and volume of used water per hour to identify the hours of maximum water demand. The peak hour in a building was defined by Buchberger *et al.* (2017) as " i) the hour of maximum water consumption or ii) the hour with the highest number of water use events", and they stated that in any given building, these two conditions often happen during the same hour, but their joint occurrence is not assured.

The frequency of water usage based on volume of water use and the number of water use events per hour were calculated for 11 days (D1, D2, …D11) and the results are shown in Figures 5-36, 5-37 & 5-38 . The results show similar frequency patterns for both the number of water activities and volume of water consumption. Additionally, the outcomes depict a diurnal water distribution of maximum water use during mid-day with peak hour during lunchtime between 11:00 – 14:00 in all the buildings. This is unlike residential buildings, which usually experience their peak during the morning. This conclusion will help future studies to focus on working hours, in particular lunch time, to find the maximum demand flow in similar buildings.

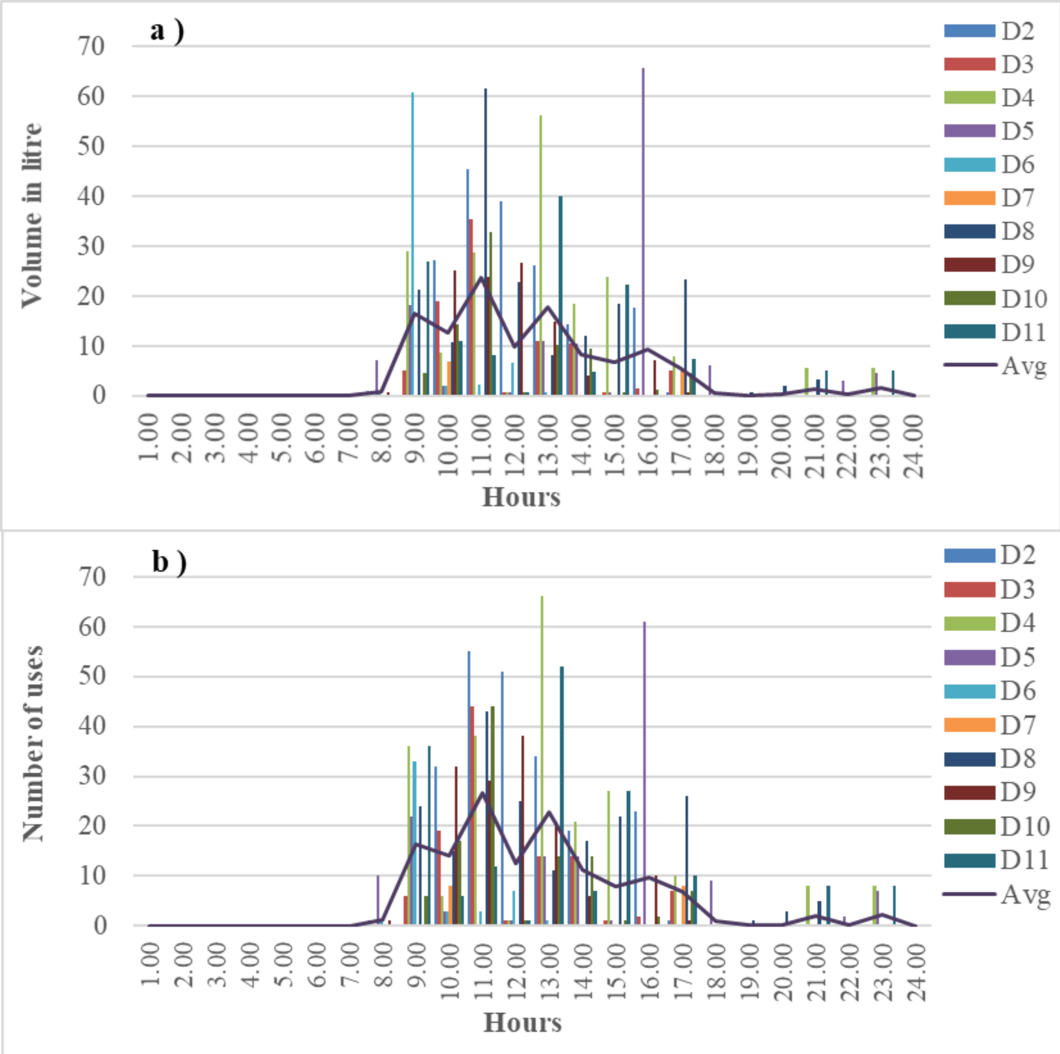


Figure 5-36 Frequency of water usage in the Estates Building by a) volume b) water use events

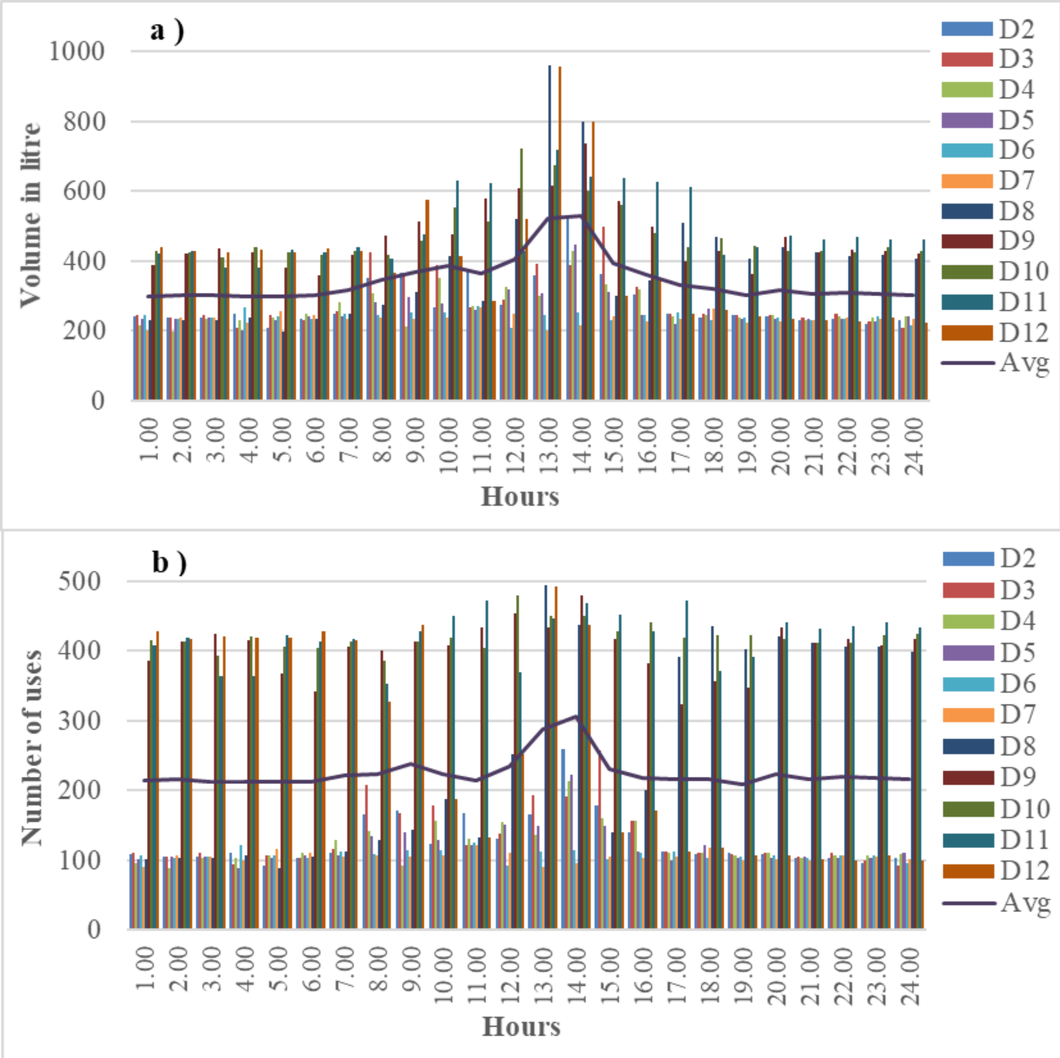


Figure 5-37 Frequency of water usage in the Postgraduate Centre by a) volume b) water use events

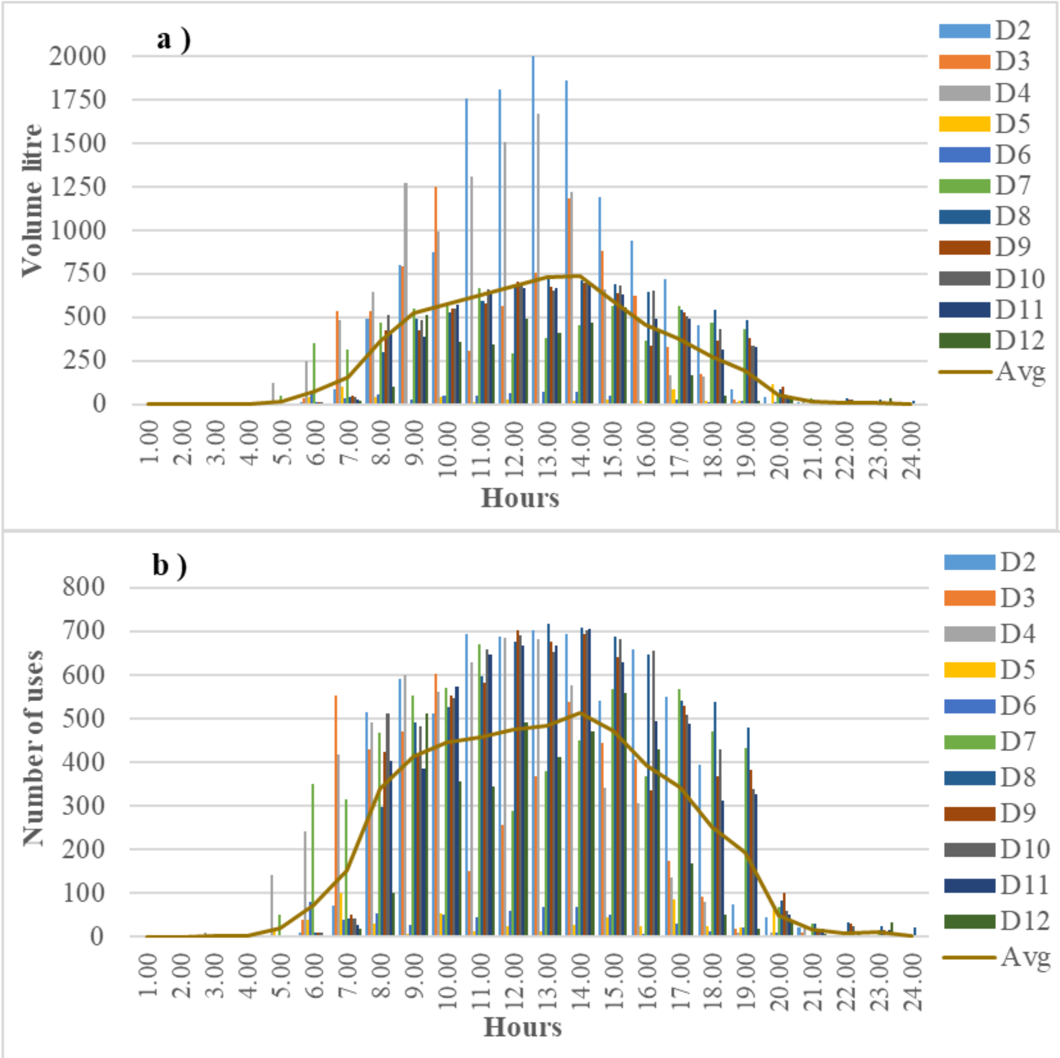


Figure 5-38 Frequency of water usage in the Hugh Nisbet Building by a) volume b) water use events

5.6 Conclusion

Recording in-situ flow measurements has been an important part of this study as the collected data can be used not only to validate the developed model, but also to understand water usage patterns in this type of building and assess the validity of current design guides. For this purpose, three buildings were selected: the Estates Building, the Postgraduate Centre and the Hugh Nisbet Building; all situated on the Heriot-Watt campus at Riccarton. Once all of the data collection requirements had been fulfilled (such as getting permission to access the building, liaising with technicians, providing ethical and risk assessment reports, and testing flowmeters), the water flow measurement started with the installation of the ultrasonic flowmeter Portaflow P330. The measurements were undertaken in the busiest period, when the buildings were occupied by the maximum number of students and staff, to record maximum demand flow. Water demand on a per second basis (5 seconds) was recorded to capture the simultaneous usage of all sanitary appliances over a two-week duration. Recording demand flow for two weeks provided a general understanding of water demand patterns in this type of building and revealed demand flow variation during the day, night, weekdays and weekends. It is worth mentioning that we believe that this is the first time in the UK that water demand has been measured at such high resolution (5 seconds) in non-residential buildings.

After analysing the data, firstly, the result provided the true values of Q'_{max} , $Q'_{0.99}$ and Q'_{avg} which are essential for validation of the WDEM. This data can also be used to assess the performance of the current design guides and the scale of overestimation of design flow. Secondly, the results illustrate the water usage patterns in the case study buildings and the diversity between the Estates, Postgraduate Centre and Hugh Nisbet buildings. The similarity in diurnal water usage patterns among the buildings confirms that the data can be used to validate the model and any further analysis regarding water demand in workplaces. Thirdly, the result clearly demonstrated that the lunch time hours, between 11:00 and 14:00, can be considered as peak hours, and any further investigation should focus on this period to determine maximum flow demand in workplaces.

Chapter 6 Validation of WDEM and comparison of observed, design and simulated flow rates

6.1 Introduction

As discussed in Chapter 5, it is important to validate the WDEM model using flow data gathered from in-situ tests. This is important not only to ensure the model's effectiveness and its impact on reducing any overestimation of design flow but also to identify any limitations of the model and make necessary improvements. For this purpose, information on sanitary appliances and user data were collected from three case study buildings: the Estates, Postgraduate Centre and Hugh Nisbet buildings on the Heriot Watt University campus.

While this chapter focuses on validation of the model, it also outlines the scale of overestimation introduced by using current UK design standards and guides. The successful application of the WDEM to estimate demand flow is demonstrated by undertaking three investigations: firstly, validation of the model's methodology through the application of information on sanitary appliances to simulate design flow rate. Here, observed flow rate data were used to validate the simulated outcomes predicted for each case study building. The results showed good overall agreement, with percentage differences of 6%, 33% and 36% for the Estates, Postgraduate Centre and Hugh Nisbet buildings respectively. Secondly, the observed flow rates were used to validate the final design equations derived specifically for workplaces. An excellent correlation confirms the accuracy of the model in estimating flow rate for these types of building. Thirdly, the scale of overestimation of demand flow introduced by using recommended design guides is provided. This was confirmed by calculating design flow rates based on the British Standards BS 8558 and the CIPHE design guide, then comparing the results with observed flow rates. The outcomes show that the design guides for this type of building result in an overestimation in demand flow of average 187%, 280%, and 291% in the Estates, Postgraduate Centre and Hugh Nisbet buildings respectively.

This chapter also analyses the final results and compares design, simulated and observed flow rates to demonstrate how the new model improves the accuracy of demand flow estimation. It shows the scale of reduction in the overestimation of demand flow enabled through using this new approach and confirms the successful performance of the WDEM in estimating design flow rates for workplace buildings.

6.2 Validation of the WDEM for workplace buildings

To evaluate the overall effectiveness of the WDEM model and to validate the methodology adopted in the model, the data collected from three workplace buildings were used, i.e. the Estates Building, the Postgraduate Centre and the Hugh Nisbet Building. Validation of the model was undertaken using the information on sanitary appliances from the case study buildings, irrespective of the number of users, i.e. the exact number and type of appliances were manually entered into the model. This was done to validate the methodology of the model and to confirm its performance in estimating demand flow specifically for these three buildings. In this stage, any errors were minimised by avoiding assumptions related to the number and type of appliances and number of persons within the buildings.

6.2.1 Simulated flow rate for the three case study buildings

In order to validate the effectiveness of the general form of the WDEM model, demand flow was simulated based on the information collected from the three case study buildings. The information needed to run the simulation includes the number and type of sanitary appliances with corresponding measured flow rate, q, and p-value. The input parameters for the case study buildings are summarised in Tables 6-1, 6-2 and 6-3. The details of the measurement and design considerations were discussed in chapters 4 & 5.

Table 6-1 Appliance information in the Estates building

Type of appliance	Number	Flow rate *l/sec*	Flow rate *l/m*	*p*-value (from CIPHE)
WC	9	0.053	3.19	0.100
Wash hand basin				
-Separate tap	3	0.098	5.87	0.055
-Mixer tap	5	0.049	2.92	0.055
Urinal	2	0.55	3.33	0.100*
Kitchen Sink				
-Separate tap	3	0.193	11.55	0.100
-Mixer tap	2	0.133	7.95	0.100
Shower	1	0.075	4.5	0.167
Cleaners' sink	1	0.13	7.8	0.017
Dishwashing machine	1	0.083**	5.0	0.005
Total	**27**			

* *p-value assumed as WC*

*** measurement was not possible, q &p obtained from other sources*

Table 6-2 Appliance information in Postgraduate Centre

Type of appliance	Number	Flow rate *l/sec*	Flow rate *l/m*	*p*-value (from CIPHE
WC	24	0.053	3.18	0.100
Bidet	2	0.15	9.0	0.055
Wash hand basin				
-Separate tap	18	0.057	3.42	0.055
-Mixer tap	4	0.083	5.0	0.055
Urinal	10	0.055	3.33	0.100*
Kitchen Sink				
-Separate tap	-	-	-	-
-Mixer tap	4	0.133	7.95	0.100
Shower	2	0.101	6.06	0.167
Cleaners' sink	4	0.13	7.8	0.017
Dishwashing machine	1	0.083**	5.0	0.005
Total	**69**			

* *p-value assumed as WC*

*** measurement was not possible, q &p obtained from other sources*

Table 6-3 Appliance information in Hugh Nisbet Building

Type of appliance	Number	Flow rate *l/sec*	Flow rate *l/m*	*p*-value (from CIPHE)
WC	45	0.053	3.19	0.100
Wash hand basin				
-Separate tap	28	0.083	5.0	0.055
-Mixer tap	44	0.049	2.92	0.055
Urinal	18	0.055	3.33	0.100*
Kitchen Sink				
-Separate tap	14	0.15	9.0	0.100
-Mixer tap	5	0.133	7.95	0.100
Cleaners' sink	5	0.13	7.8	0.017
Dishwashing machine	6	0.083**	5.0	0.005
Total	**165**			

* *p-value assumed as WC*

** *measurement was not possible, q &p obtained from other sources*

Once all the information had been applied within the WDEM, the model was run to simulate the design flow for each case study building. As described in detail in Chapter 4, the model was run 400,000 times to determine outcomes for all possible water usage events and to estimate demand flow for all simultaneous water usage. After generating the CDF for all possible flows in accordance with their probabilities (from 0% to 100%), the demand flow rate for the 99th percentile (Q_{99}) was obtained. As discussed previously, this study focuses on the 99th percentile as the basis for prediction of design flow. Figures 6-1, 6-2 and 6-3 show the resultant CDFs for flow rate and determination of Q_{99} for all three case study buildings. The values of simulated flow rates Q_{sim} for different levels of reliabilities were recorded, including the average, Q_{avg}, 99th percentile, Q_{99}, and maximum, Q_{max}, Table 6-4. The values of Q_{99} were considered as the new design flow rates, Q_d, to be used for comparison with flow rates obtained both from measurement and from design guides.

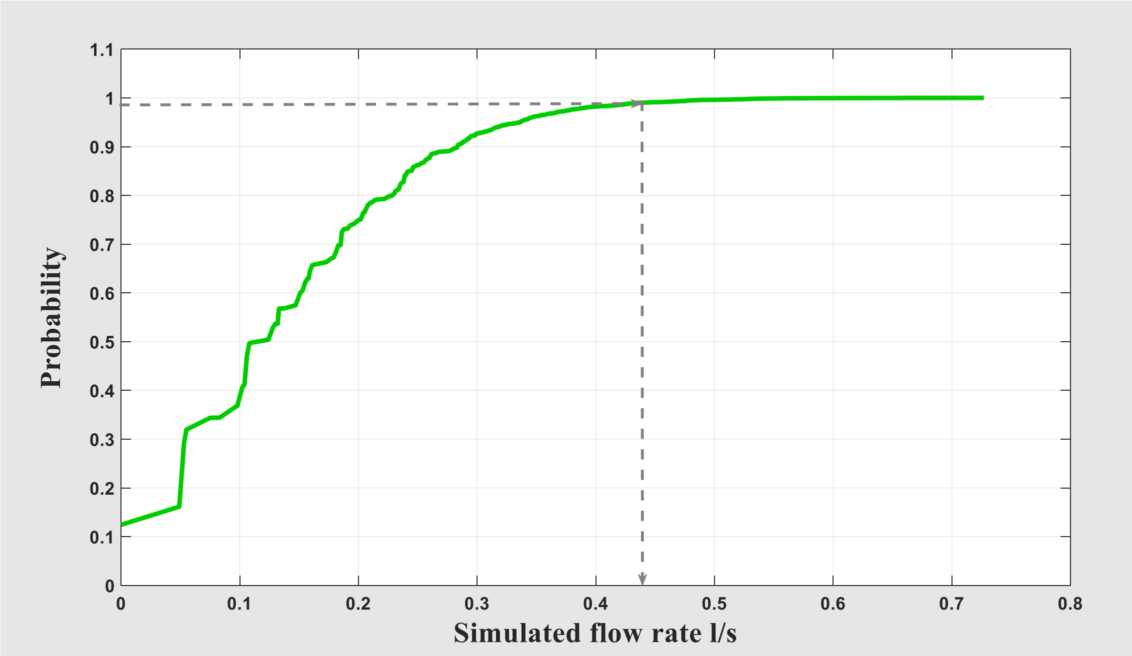


Figure 6-1 The CDF for simulated flow rates and extraction of Q_{99} in the Estates Building

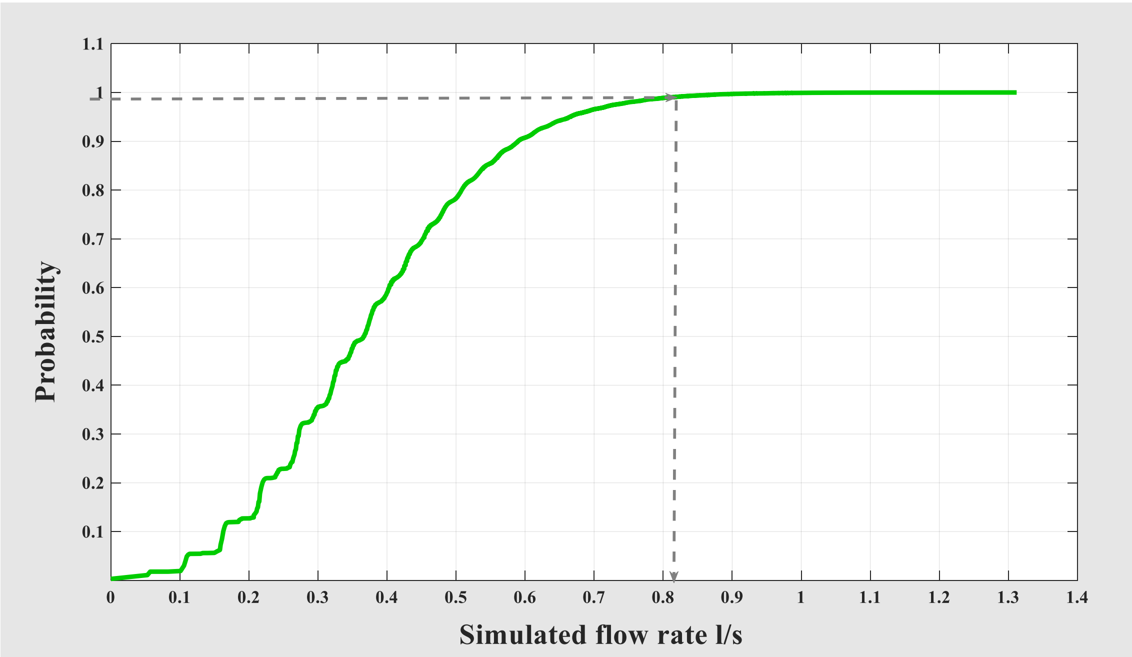


Figure 6-2 The CDF for simulated flow rates and extraction of Q_{99} in the Postgraduate Centre

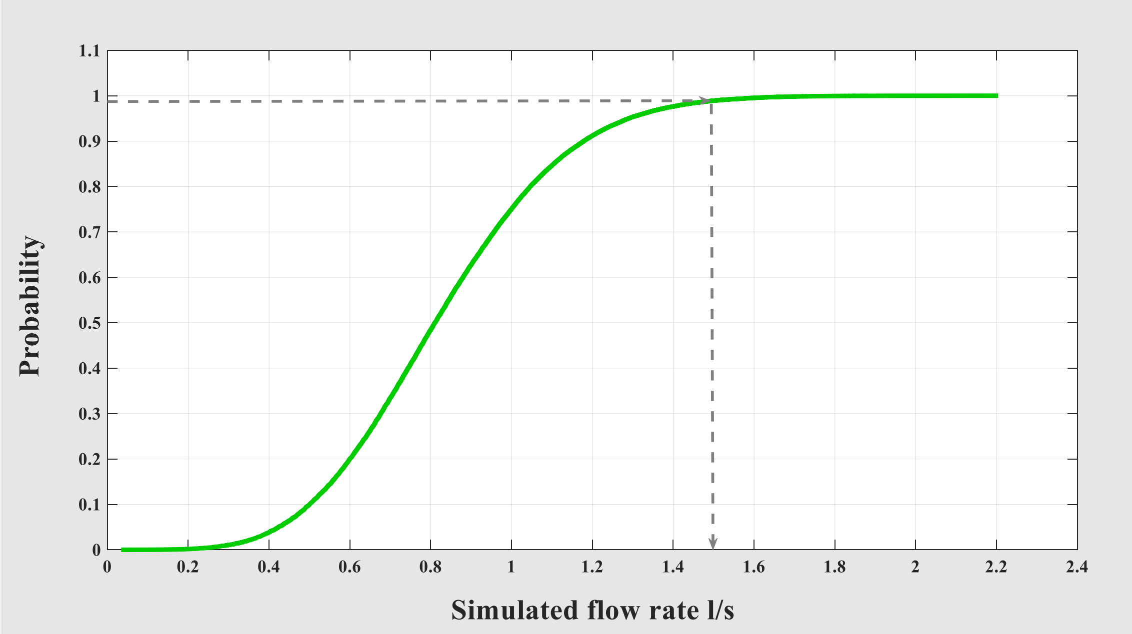


Figure 6-3 The CDF for simulated flow rates and extraction of Q_{99} in the Hugh Nisbet Building

Table 6-4 The values of Q_{avg}, Q_{99} and Q_{max} for the case studies buildings

Case study buildings	Q_{sim} l/s		
	Q_{avg}	Q_{99}	Q_{max}
Estates building	0.140	0.437	0.707
Postgraduate Centre	0.373	0.823	1.312
Hugh Nisbet building	0.828	1.511	2.204

6.2.2 Validation of the model based on observed flow rate

To validate the model, comparisons were made with flow data recorded in each of the case study buildings. Measured flow rate Q'_{obs} was recorded using ultrasonic flowmeters at 5 second intervals. The method of measurement was discussed in Chapter 5, while the key information, including Q'_{avg}, Q'_{99}, and Q'_{max}, is summarised in Table 6-5, below. Figures 6-4, 6-5, and 6-6 show a comparison between the simulated and observed flow rates for the Estates, Postgraduate Centre and Hugh Nisbet buildings respectively.

Table 6-5 Observed flow rate in the case study buildings

Case study buildings	Q'_{obs} l/s		
	Q'_{avg}	Q'_{99}	Q'_{max}
Estates building	0.171	0.423	0.691
Postgraduate Centre	0.309	0.618	0.980
Hugh Nisbet Building	0.368	1.111	1.617

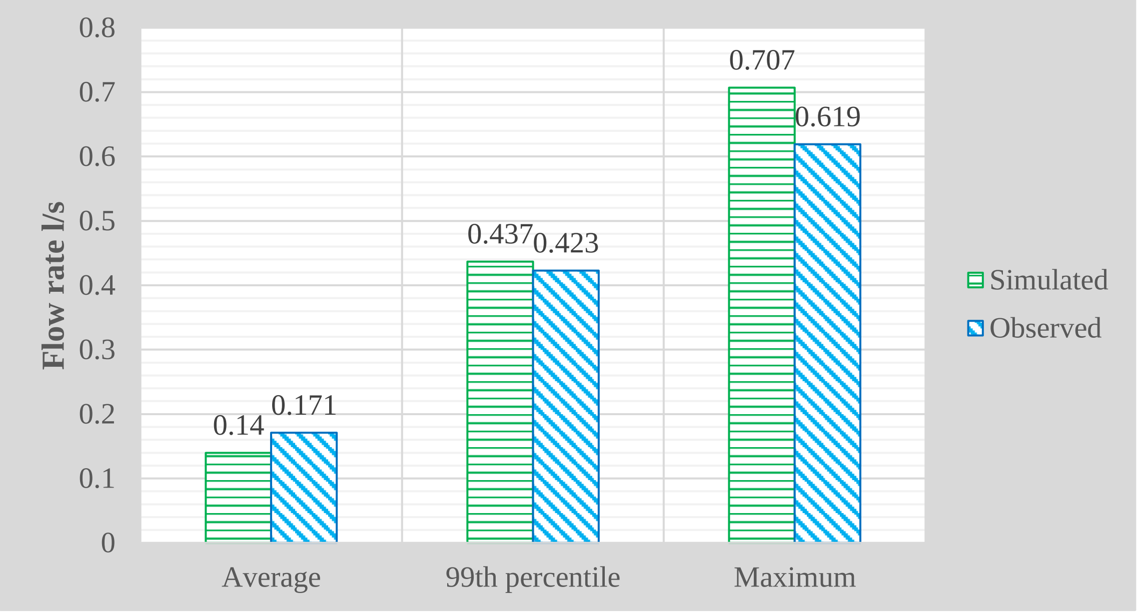


Figure 6-4 Comparison of simulated and observed flow rates in the Estates Building

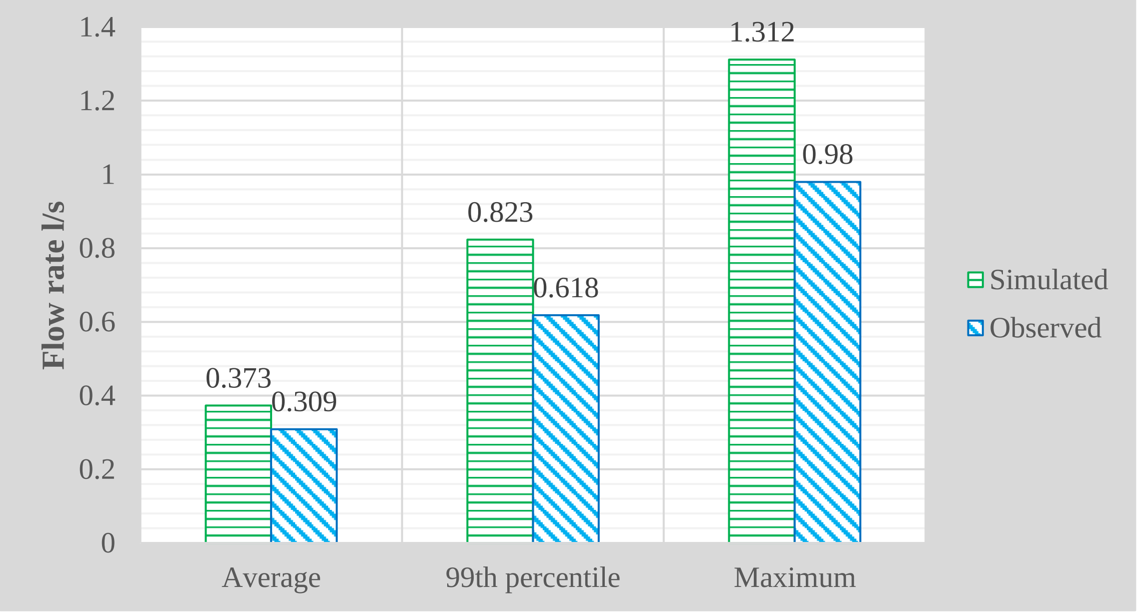


Figure 6-5 Comparison of simulated and observed flow rates in the Postgraduate Centre

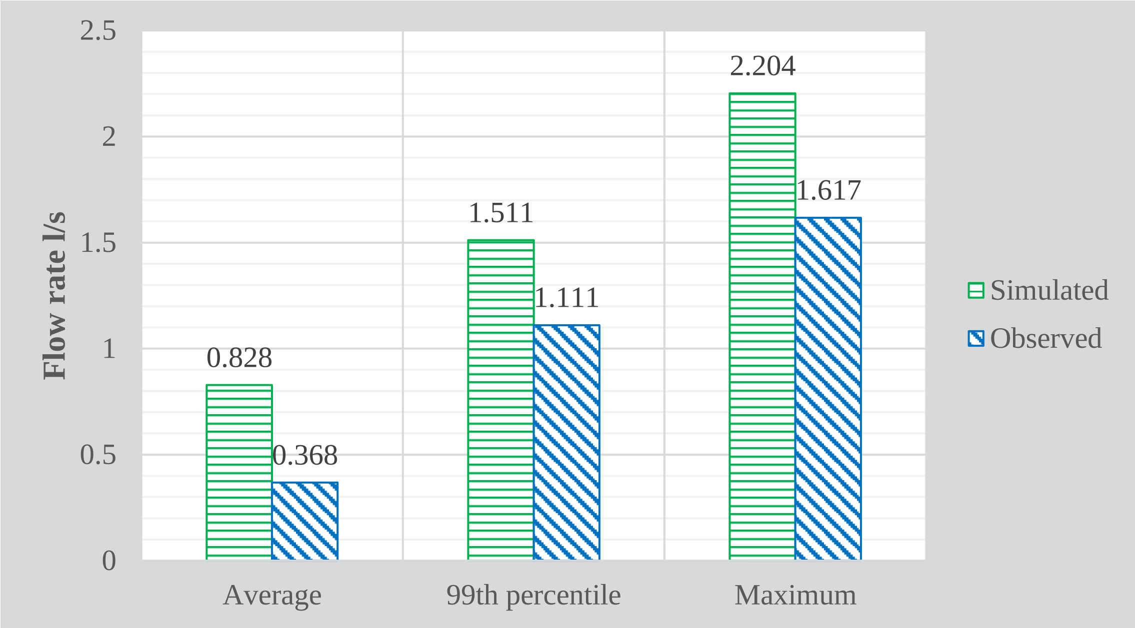


Figure 6-6 Comparison of simulated and observed flow rates in the Hugh Nisbet Building

From the figures above, the following conclusions can be drawn:

i. it can be seen that the WDEM is generally capable of estimating the design flow rate for all buildings relatively well. The model does yield a slightly different level of accuracy for each building, but the figures show that this discrepancy allows the designer to err on the safe side, as the simulated flow does not fall below the observed flow.

ii. the simulated demand flow is very close to the observed flow rate, especially for small-scale buildings such as the Estates building, where the predicted design flow is only 4% greater than the observed flow. However, with increasing scale, the WDEM yields a higher demand flow when compared with the observed data; here, the model predicted an uplift of 33% and 36% for the Postgraduate and Hugh Nisbet buildings respectively.

iii. these results confirm the effectiveness of the WDEM for this type of building. Further analyses such as comparison of simulated, observed and design flow rates were required to enhance understanding of the model's performance and are discussed in the following sections.

6.3 Validation of the design equations for workplaces

In addition to validation of the WDEM, the observed flow rate data were also used to validate the design equations derived for workplaces. While the results presented in the previous section confirm the effectiveness of the model for this type of building, the derived design equations also need to be examined in order to ensure that all assumptions related to the number of users and provision of sanitary appliances were made appropriately. For the case study buildings, the number of occupants was determined using a 'people counter' or manually. The records showed that the average number of people in the case study buildings at the busiest time during the period of flow rate measurements, more specifically around midday, was approximately 50, 450, and 1200 for the Estates, Postgraduate Centre and Hugh Nisbet buildings respectively. This information was used to calculate the provision of sanitary appliances as discussed in chapters 3 and 4. As discussed in section 4.6, five design equations were obtained based on appliance water efficiency as classified by the European water labelling scheme.

The sanitary appliances installed in all three case study buildings can generally be classified as water efficient models, close in terms of consumption to group A. As shown in Table 6-6, most of the appliances (85%) in the Postgraduate Centre and Hugh Nisbet buildings best matched with group A. Thus, the measured flow rate in these two buildings needs to be compared with the design line A. However, in the Estates building there are different appliances which can be classified under Group A, B and C. The Estates building, therefore, should be compared with the design line B, or somewhere between lines B and C.

Table 6-6 Classification of sanitary appliances based on flow rate and efficiency levels in the case study buildings

Appliances	Estates				Postgraduate			Hugh Nisbet		
	No	*q l/m*			No	*q l/m*		No	*q l/m*	
		A	B	C		A	B		A	B
WC	9	3.2			24	3.2		45	3.1	
Bidet					2		9			
Wash hand basin										
-Separate tap	3		5.9		18	3.4		28	5	
-Mixer tap	5	2.9			4		6.4	14	2.9	
Urinal	2	3.3			10	3.3		18	3.3	
Kitchen Sink										
-Separate tap	3			11.5				14		9
-Mixer tap	2		8		4		8	5		7.9
Shower	1	4.5			2		6.1			
Cleaners' sink	1		7.8		4		7.8	5		7.8
Dishwashing machine	1	5.0			1	5		6	5	
Percentage%		**67%**	**22%**	**11%**		**84%**	**16%**		**85%**	**15%**

To validate the best-fit equations, which represent the design determination, the measured flow rates for all case study buildings were plotted as shown in Figure 6-7. Similar to the validation exercise discussed in the previous section, the results show that there is a good agreement between the design lines and measured flow rates for all case study buildings. Design line A is very close to the measured flow rate in both the Postgraduate Centre and the Hugh Nisbet building, and design line B is close to the measured flow rate for the Estates building. It should be noted that the design values are slightly higher than the measured flow rate for all buildings, exceeding measured flow rates by only 6%, 10% and 7% in the Estates, Postgraduate and Hugh Nisbet buildings respectively.

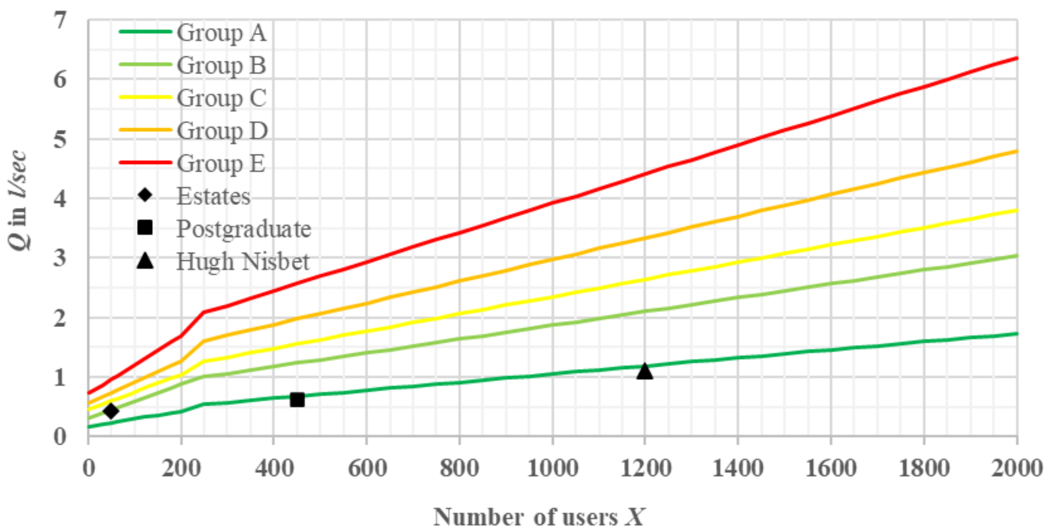


Figure 6-7 Validation of design equations with measured flow rate

6.4 Comparison between design, simulated and observed flow rates

In order to provide a comprehensive understanding of the results of this study and present a full picture of water demand analysis, a comparison between design, simulated and measured flow rate data was undertaken. This comparison reveals the scale of overestimation introduced by using current UK design guides and confirms the effectiveness of the new model and design equations. The simulated flow rate values established using the WDEM and the actual flow demand recorded from in-situ measurements were discussed in chapters 4 and 5 respectively, while the design flow rate based on the current guides is discussed below.

6.4.1 Calculating design flow rate based on the current guides

The design standards and guides for estimating flow demand in the UK were discussed in chapter 2, where the most recent version of the British Standard, BS 8558, recommends the use of BS EN 806-3 for designing water systems in residential buildings and using the ‘traditional’ approach for non-residential buildings. Chapter 2 also notes the lack of research on the suitability of these design guides when applied to non-residential buildings. Thus, demand flow for the case study buildings was calculated using the recommended design standards and guides (BS 8558 and CIPHE). This enabled a wider assessment of the performance of these guides when applied to non-residential buildings.

To calculate the design flow rate (Q"), the standards most commonly used in the UK, namely BS 8558 and the CIPHE guide were used. The information on sanitary appliances installed in the case study buildings was recorded during flow rate measurements as discussed in chapter 5 (see Table 5-1). This information was obtained initially from floor plans and manufacturers’ manuals or from an internet search but was then checked by visiting the buildings to confirm the count as installed and to measure their discharge manually. Based on these design guides, the total LUs were calculated for each case study building as shown in Table 6-7. After calculating the total LUs, the design flow rate Q'' was calculated from graphs available in the design guides. Figures 6-8, 6-9, and 6-10 show the design flow rates obtained from the two design guides for the Estates building, the Postgraduate Centre and the Hugh Nisbet Building respectively. The detail of the calculations is available in Appendix C.

The results demonstrate that there is no significant difference between BS 8558 and CIPHE, and the flow rates obtained from these two guides are very close to each other for all case study buildings.

Table 6-7 Total LUs for all case study buildings

Design guides	Total LUs		
	Estates building	Postgraduate Centre	Hugh Nisbet Building
BS 8558	99	225	552
CIPHE	99	236	520

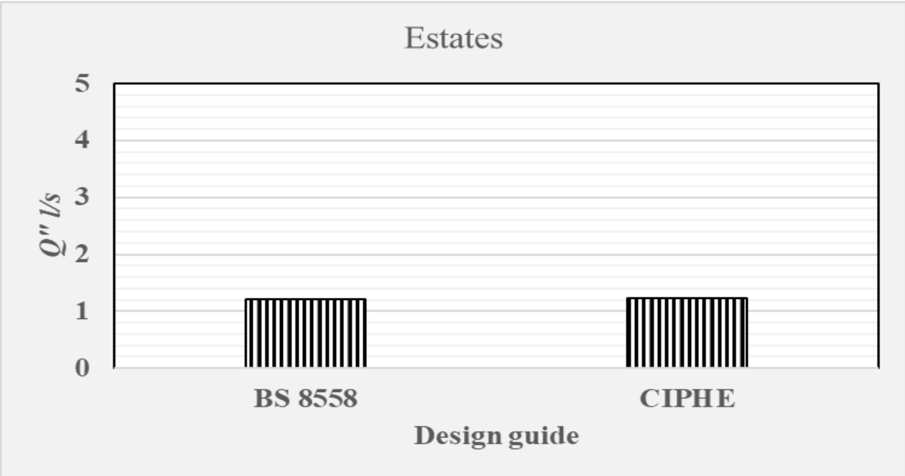


Figure 6-8 Design flow rate Q" for Estates building

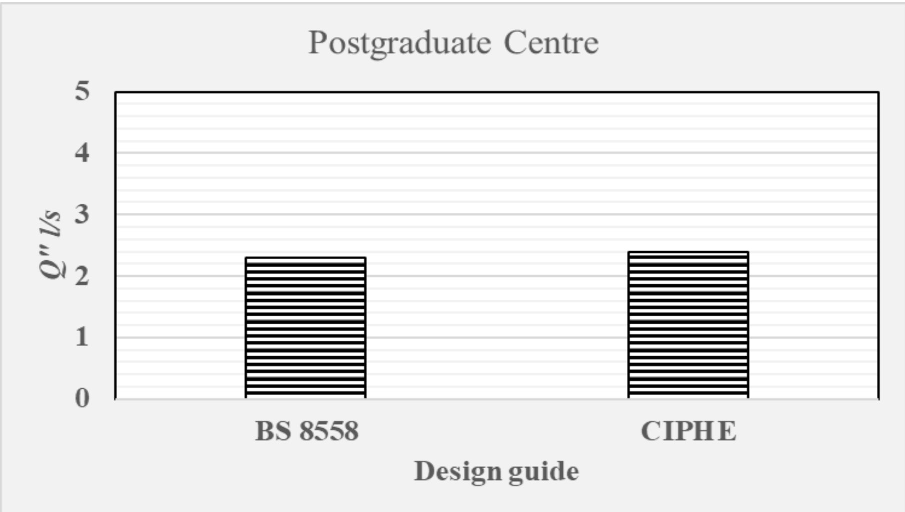


Figure 6-9 Design flow rate Q" for Postgraduate Centre

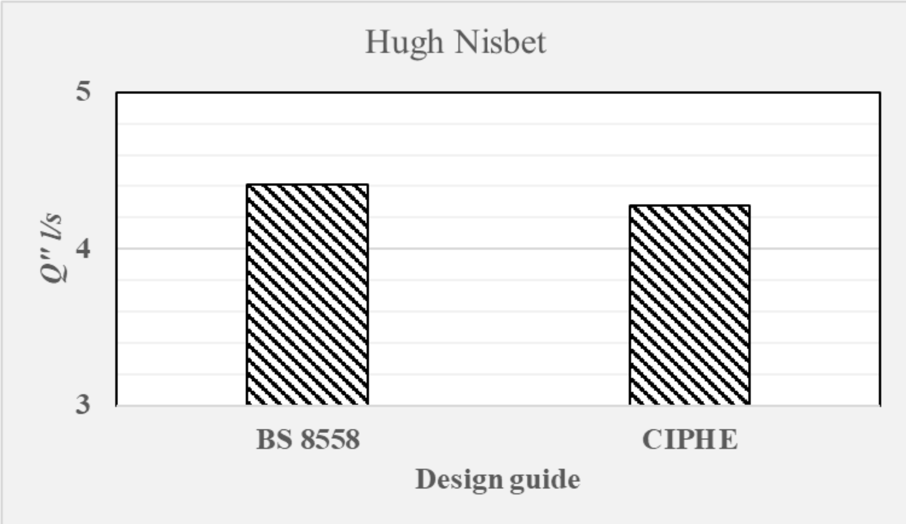


Figure 6-10 Design flow rate Q" for Hugh Nisbet Building

6.4.2 Comparing simulated flow rate with design and observed flow rates for the case study buildings

The comparison of design, simulated and observed flow rates for the case study buildings can be defined as a crucial part of water demand analysis because it not only helps to explain the scale of overestimation introduced by current design guides but also illustrates the effectiveness of the WDEM model in predicting demand flow and its impact in reducing the oversizing of water systems. Table 6-8 summarises the values of design, simulated and measured flow rates for the case study buildings and Figure 6-11 shows a direct comparison. As expected, both design codes are very close to each other and produce significantly greater values than the measured flow rate. Figure 6-11 clearly shows the scale of overestimation introduced by using BS8558 and the CIPHE Guide. The CIPHE Guide, which provides a variety of LUs for non-residential buildings, resulted in an overestimation of demand flow by 188%, 288% and 285% in the Estates, Postgraduate Centre and Hugh Nisbet buildings respectively. The BS 8558 also resulted in an overestimation of demand flow by 186%, 271% and 297% in the three buildings respectively. In contrast, the results confirm the effectiveness of the WDEM model in estimating demand flow in all buildings. The design guides resulted in an overestimation in flow rate of 178%, 185%, and 187% compared to flow rate obtained from the model in the three case study buildings. This confirms that in general, the flow rate estimated by the WDEM is significantly closer to the measured rate for all three case study buildings.

Table 6-8 Design, simulated and measured flow rates in case study buildings

Case study buildings	Number of persons	Flow rate *l/s*			
		Design Q''		Simulated Q'	Measured Q
		BS 8558	CIPHE		
Estates building	50	1.21	1.22	0.437	0.423
Postgraduate Centre	450	2.29	2.40	0.823	0.618
Hugh Nisbet building	1200	4.41	4.28	1.511	1.111

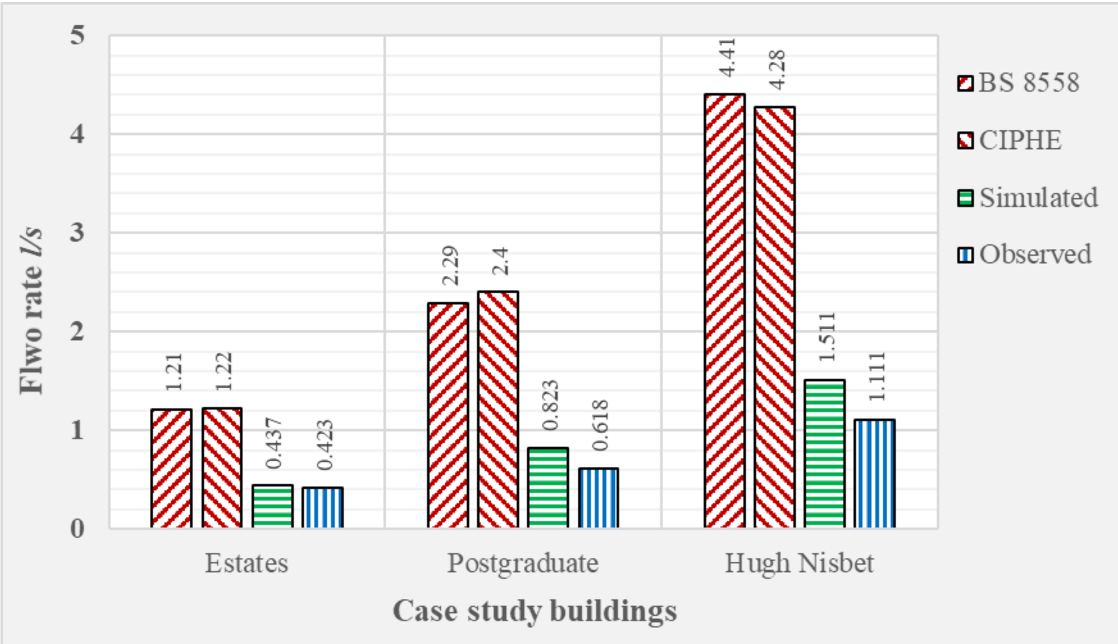


Figure 6-11 Comparison of design, simulated and measured flow rate in the case study buildings

6.4.3 Comparing final design equations with design and observed flow rates

Comparing the WDEM design equations with measured and guide-derived design flow rate provides a comprehensive understanding of water demand results. This comparison demonstrates this study's successful application of the model and accuracy of the final design equations for water demand estimation.

Figure 6-12 shows the WDEM design lines alongside measured flow rate and the design flow rate obtained from the BS 8558 and the CIPHE design guides. As expected, the design lines for group A and group B are significantly less than the design flow rate obtained by the design guides. Despite the WDEM-design lines being slightly greater than observed rate, they can be applied to workplaces to allow a significant reduction in design flow. The scale of reduction in the demand flow was 178%, 185% and 187% for the Estates, Postgraduate Centre and Hugh Nisbet buildings respectively. These results provide much needed recommendations concerning the selection of design guides for non-residential buildings and highlight the need to update design information for better estimation of demand flow. This approach, therefore, can be described as a valuable technique in estimating demand flow and reducing the extent of the oversizing problem.

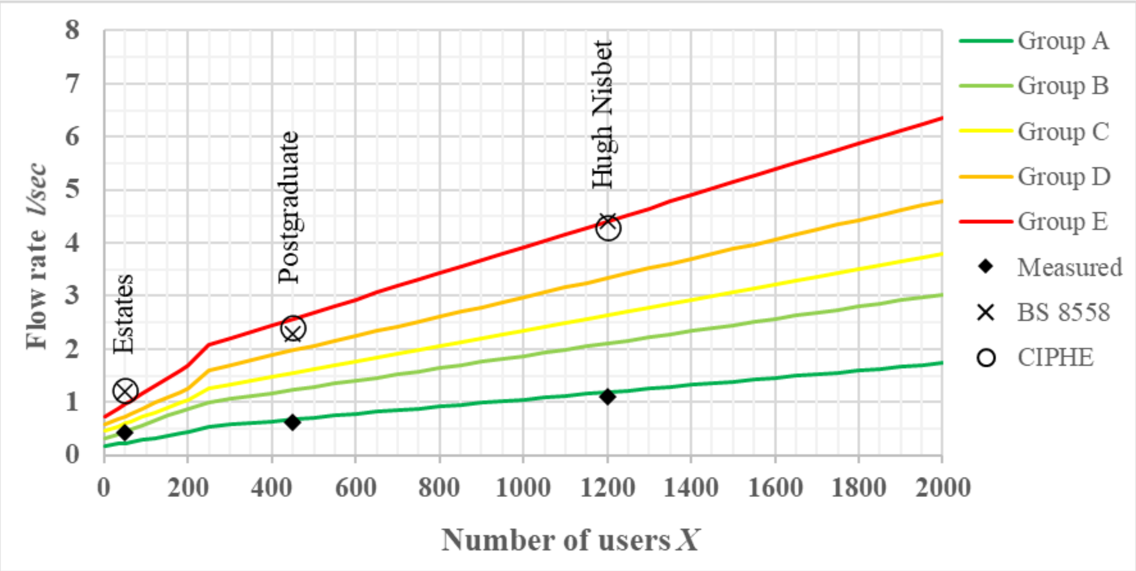


Figure 6-12 Comparing the design equations with design and measured flow rate

6.5 Conclusion

To confirm the accuracy of the WDEM, it is crucial to quantify and describe the validity of the model and its resultant design equations. Undertaking validation of the model provides essential information on the effectiveness of the approach in predicting demand flow in workplace buildings. Establishing predictive accuracy also provides important information on the limitations and strengths of the approach as well as identifying areas for future improvements. This chapter has provided an in-depth review of the validation process, undertaken by comparing simulated flow rate with measured flow data recorded in three case study buildings, i.e. the Estates, Postgraduate Centre and Hugh Nisbet buildings. It has also demonstrated the scale of overestimation introduced by using current UK design guides.

As discussed in previous sections of this chapter, the model was run to simulate flow rate for each case study building using the information on the installed water appliances to validate the methodology of the general form of the WDEM. A comparison between simulated and observed flow rate was then undertaken for all case study buildings. The results show a good agreement between the model outputs and site measurements. The measured flow data were also used to validate the final design equations derived for workplace buildings. The results show that the measured flow data were very close to design lines A and B which were best matched to the case study buildings. In general, the new design equations yield a slightly increased demand flow; 6%, 10% and 7% for the Estates, Postgraduate Centre and Hugh Nisbet buildings respectively. These small differences confirm the accuracy and workability of this novel approach in estimating demand flow rate for this type of building. The final step in the validation process was to compare the simulated, measured and design flow rates calculated from the BS8558 and CIPHE design guides. This comparison demonstrated the effectiveness of the method for water demand estimation since it resulted in respective reductions in the design flow rate of 172%, 253% and 260% for the Estates, Postgraduate Centre and Hugh Nisbet buildings. These outcomes confirm that this novel approach can be defined as a promising development in water estimation modelling and suggest that using the WDEM for workplace buildings will enable a reduction in the current oversizing of water network systems and improve energy efficiency, health consequences and sustainability.

Chapter 7 Conclusion and recommendations

7.1 Overview

This research has developed a new approach for the estimation of demand flow for non-residential buildings. Recent national and international studies have confirmed that current design codes and guides for estimating demand flow in modern plumbing systems result in oversizing of the whole system, including pipes, water storage, boilers and booster pumps. Despite considerable changes in sanitary appliance efficiency and user behaviour, commonly-adopted design methods still use the same traditional loading unit method that has been in place for many decades. Just as it is important to focus on reducing water consumption, it is also important to make sure there is a correct system to deliver an adequate supply of high-quality water to customers, that takes into account efficiency, sustainability and health consequences.

Based on the fact that accurate demand flow estimation is key in designing efficient and sustainable water systems, this study has developed a new method for better estimation of demand flow. This was done through the development of a stochastic model underpinned by the application of the binomial distribution as a statistical framework and by use of the Monte Carlo technique as a computational algorithm to simulate demand flow. In addition, high quality flow data were measured for the purposes of validation. Specifically, this study provides a new design approach for workplace buildings.

Before developing the model, an extensive review was carried out of the most recent research in this field. Critical assessment and scientific investigation were undertaken to reveal the advantages and limitations of previous modelling approaches and to justify the use of a stochastic model to estimate demand flow specifically for workplace buildings. This decision was made based on the fact that since this model depends on statistical information on users and sanitary appliances instead of flow rate data, it can be readily updated and adapted to future changes. The model can also estimate flow rate for different levels of system reliability.

For the purposes of model validation, ultrasonic flowmeters were installed in three workplace buildings and the in-situ flow rate was recorded every 5 seconds for around two weeks. These data were used not only to validate the accuracy of and confidence in the model but also to understand water usage patterns in workplace buildings. In addition to flow rate data, information on sanitary appliances and users was recorded. Furthermore, establishment of the correlation between the number and type of sanitary appliances and number of users in the buildings provided a framework to enable an appropriate provision of appliances based on number of users. This correlation permitted a reduction in the variables used in the final design equations and a determination of demand flow depending on number of users only. Key findings are highlighted in the following sections.

7.2 Key findings

7.2.1 New design approach to estimate demand flow

Introducing a new design approach to estimate demand flow represents the main contribution of this work. Only a limited number of previous studies have addressed demand flow and water usage patterns in non-residential buildings, and this work is the first known study to systematically investigate water demand and quantify the oversizing problem in workplace buildings. Thus, the successful application of the WDEM model has provided confidence that the approach has the potential to provide a base for water demand modelling and to be considered as the first step in deriving new design equations for all other types of non-residential buildings. The main features are:

i. developing a new stochastic model to estimate design flow rate for non-residential buildings. The technique adopted here can be described as a novel approach in demand flow estimation. In addition to the model's accuracy, it is worth noting the flexibility and adaptability of the WDEM to enable adaptation to future changes in water usage habits or the design of sanitary appliances.

ii. derivation of new equations for the calculation of design flow rate for workplace buildings based on the number of occupants. Validation of the model using in-situ flow rate data has confirmed both the effectiveness and applicability of the method. The results confirm the impact of this approach in reducing the overestimation of design flow rate introduced by current design codes and guides.

iii. final design equations that can be used for various scales ranging from small to large workplaces. Determining design flow rate can be achieved through reference to the number of users in the building. Reliance on the number of users as the main variable underpinning the design equations and as the reference for the provision of sanitary appliances helps accommodate those appliances installed in the building for reasons such as architecture or designer's judgement, or for the installation of additional appliances to meet future demand.

iv. generating five design equations to cover all types of sanitary appliances based on water efficiency levels. These equations will help designers avoid having to make unnecessary judgement calls, especially given that most available sanitary appliances available on the market are supplied with known water efficiency levels.

7.2.2 Water demand patterns

An important part of this research has involved gathering data on users, sanitary appliances and demand flow. In addition to using this data to develop the model and validating its effectiveness in the estimation of demand flow, the data were also used to analyse and understand water usage patterns in workplace buildings. It is worth mentioning that it is understood that this is the first time in the UK that water demand has been measured at such high resolution (5 seconds) in non-residential buildings. These data sets show:

i. the hours between 11:00 and 14:00 can be considered as peak hours for workplace buildings, displaying a maximum frequency of water usage in terms of volume of water and number of water usage events. This will help researchers focus on this time window for any future investigation of water demand patterns and maximum demand flow.

ii. the design flow rate obtained from recommended design guides was almost double compared to measured flow rate. This confirms the significance of this study and the need to develop a new design approach for non-residential buildings.

7.3 Limitations and future work

Given the importance of water efficient appliances, the design equations were classified into five groups (A, B, C, D, and E). Using each design equation to estimate water demand should produce accurate results for each specific group of appliances when the flow rate of all appliances is matched to the flow rate range defined for the individual group (A to E). However, the WDEM design equations may not be able to accurately estimate design flow rate for a mixed group of appliances with differing water efficiency levels. In this case, there are two options: selecting the flow rate value that falls between the design lines based on the designer's judgement, or adding a new sub-type of appliances and running the WDEM model for all appliances with these new flow rates.

Although the WDEM model yields an accurate estimation of demand flow, the model can be improved by fine-tuning its input parameters and reducing assumptions. For example, some assumptions were made for the number of kitchen sinks, cleaning sinks and dishwashers when establishing the number of users and the provision of sanitary appliances. Slightly higher numbers of these appliances were used in the simulation to cope with any unanticipated demand, whereas more detailed data on the provision of these appliances will mean the method will be more reliable.

The results of this study were compared and validated with data collected in 2019 before the pandemic. This can be considered as a good achievement because demand flow was measured during normal working days when the buildings were fully occupied, whereas, during COVID 19 the workplace buildings were usually occupied by less people as working from home was recommended by the government. In addition, some places decreased the number of people allowed in the building. Thus, the buildings may have been used by less people and consequently this would have resulted in lower demand flow. Despite the fact that design flow rate is predicted to decrease during situations such as the COVID 19 pandemic, this issue should be investigated in future research to reveal its effect on demand flow and water usage patterns. On the other hand, it is worth mentioning that after successful application of the WDEM to the workplace, the necessary preparation was undertaken to collect information on other types and scales of buildings and extend the application of the model. For this purpose, invitations to participate in the study were prepared and sent to some water related companies and organisations such as the Chartered Institution of Building Services Engineers (CIBSE). Unfortunately, data collection was completely halted, not just in the UK but also all around the world, due to the COVID 19 pandemic. The UK Government published a wide range of guidance relating to COVID 19 including information on the law and public health advice. According to lockdown restrictions, rules were imposed ordering people to stay home, work from home and to leave home only for essential reasons. These restrictions caused the closure of most non-residential buildings and businesses during the pandemic.

While the model can predict demand flow for any scale of building, including very large buildings, the lack of flow rate data for large scale buildings was a barrier when validating for buildings with over 2000 occupants. Thus, although the new design equations are able to effectively estimate demand flow for buildings with up to 2000 occupants, larger buildings would require new flow rate data for the purposes of validation. Despite taking into account most factors affecting demand flow in non-residential buildings, the model has thus far been applied only to the workplace and further work is required to extend its application to other types of non-residential buildings.

The WDEM can nevertheless be defined as a base approach to estimate demand flow in different types of non-residential buildings. In general, the excellent correlation between simulated and measured flow rates should encourage other researchers to apply the WDEM model to different types of non-residential buildings and make the necessary improvements to derive new design equations for such buildings. This would be the first step in removing the oversizing concern and updating the design guides for all modern water systems.

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Appendix A: Tables of pipe properties

Micronics Pipe Tables

micronics

ANSI Carbon Steel pipe schedules

(top number is wall thickness and bottom number is Kg/M)

Norminal pipe size inches	OD mm	5S	10S	10	2 0	30	STD	40S	40	60	XS	80S	80	100	120	140	160	XXS
1/8	10.30	-	1.42 0.28	-	-	-	1.73 0.37	1.73 0.36	1.73 0.37	-	2.41 0.47	2.41 0.48	2.41 0.47	-	-	-	-	-
1/4	13.70	-	1.65 0.51	-	-	-	2.24 0.63	2.24 0.64	2.24 0.63	-	3.02 0.80	3.02 0.82	3.02 0.80	-	-	-	-	-
3/8	17.10	-	1.65 0.64	-	-	-	2.31 0.84	2.31 0.84	2.31 0.84	-	3.20 1.10	3.20 1.12	3.20 1.10	-	-	-	-	-
1/2	21.30	1.65 0.82	2.11 1.01	-	-	-	2.77 1.27	2.77 1.30	2.77 1.27	-	3.73 1.62	3.73 1.65	3.73 1.62	-	-	-	4.78 1.95	7.47 2.55
3/4	26.70	1.65 1.04	2.11 1.31	-	-	-	2.87 1.69	2.87 1.71	2.87 1.69	-	3.91 2.20	3.91 2.24	3.91 2.20	-	-	-	5.56 2.90	7.82 3.64
1	33.40	1.65 1.33	2.77 2.13	-	-	-	3.38 2.50	3.38 2.55	3.38 2.50	-	4.55 3.24	4.55 3.29	4.55 3.24	-	-	-	6.35 4.24	9.09 5.45
1 1/4	42.20	1.65 1.68	2.77 2.76	-	-	-	3.56 3.39	3.56 3.46	3.56 3.39	-	4.85 4.47	4.85 4.56	4.85 4.47	-	-	-	6.35 5.61	9.70 7.77
1 1/2	48.30	1.65 1.95	2.77 3.17	-	-	-	3.68 4.05	3.68 4.13	3.66 4.05	-	5.08 5.41	5.08 5.51	5.08 5.41	-	-	-	7.14 7.25	10.15 9.56
2	60.30	1.65 2.44	2.77 4.01	-	-	-	3.91 5.44	3.91 5.54	3.91 5.44	-	5.54 7.48	5.54 7.63	5.54 7.48	-	-	-	8.74 11.11	11.07 13.44
2 1/2	73.00	2.11 3.77	3.05 5.36	-	-	-	5.16 8.63	5.16 8.81	5.16 8.63	-	7.01 11.41	7.01 19.64	7.01 11.41	-	-	-	9.53 14.92	14.02 20.39
3	88.90	2.11 4.60	3.05 6.59	-	-	-	5.49 11.29	5.49 11.52	5.49 11.29	-	7.62 15.27	7.62 15.59	7.62 15.27	-	-	-	11.13 21.35	15.24 27.68
3 1/2	101.60	2.11 5.29	3.05 7.55	-	-	-	5.74 13.57	5.74 13.84	5.74 13.57	-	8.08 18.63	8.08 19.01	8.08 18.63	-	-	-	-	-
4	114.30	2.11 5.96	3.05 8.52	-	-	-	6.02 16.07	6.02 16.40	6.02 16.07	-	8.56 22.32	8.56 22.77	8.56 22.32	-	11.13 28.32	-	13.49 33.54	17.12 41.03
5	141.30	2.77 9.67	3.40 11.82	-	-	-	6.55 21.77	6.55 22.20	6.55 21.77	-	9.53 30.97	9.53 31.59	9.53 30.97	-	12.70 40.28	-	15.88 49.11	19.05 57.43
6	168.30	2.77 11.55	3.40 14.13	-	-	-	7.11 28.26	7.11 28.83	7.11 28.26	-	10.97 42.56	10.97 43.42	10.97 42.56	-	14.27 54.20	-	18.20 67.56	21.95 79.22
8	219.10	2.77 15.09	3.76 20.37	-	6.35 33.31	7.04 36.81	8.18 42.55	8.18 43.39	8.18 42.55	10.31 53.08	12.70 64.64	12.70 65.95	12.70 64.64	15.09 75.92	18.26 90.44	20.62 100.92	23.01 111.27	22.23 107.92
10	273.10	3.40 23.09	4.19 28.34	-	6.35 41.77	7.80 51.03	9.27 60.31	9.27 61.52	9.27 60.31	12.70 81.55	12.70 81.55	12.70 83.19	15.09 96.01	18.26 114.75	21.44 133.06	25.40 155.15	28.58 112.33	25.40 155.15
12	323.90	3.96 31.89	4.57 36.73	-	6.35 49.73	8.38 65.20	9.53 73.88	9.52 75.32	10.31 79.73	14.27 108.96	12.70 97.46	12.70 99.43	17.48 132.08	21.44 159.91	25.40 186.97	28.58 208.14	33.32 238.76	25.40 186.97
14	355.60	3.96 35.06	4.78 42.14	6.35 54.69	7.92 67.90	9.53 81.33	9.53 81.33	-	11.13 94.55	15.09 126.71	12.70 107.39	35.71 281.70	19.05 158.10	23.83 194.96	27.79 244.65	31.75 253.56	35.71 281.70	-
16	406.40	4.19 42.41	4.78 48.26	6.35 62.64	7.92 77.83	9.53 93.27	9.53 93.27	-	12.70 123.30	16.66 160.12	12.70 123.30	40.49 365.35	21.44 203.53	26.19 245.56	30.96 286.64	36.53 333.19	40.49 365.37	-
18	457.00	4.19 47.77	4.78 54.36	6.35 70.57	7.92 87.71	11.13 122.38	9.53 105.16	-	14.27 155.80	19.05 205.74	12.70 139.15	45.24 459.37	23.88 254.55	29.36 309.62	34.93 365.56	39.67 408.26	45.24 459.37	-
20	508.00	4.78 60.46	5.51 70.00	6.35 78.55	9.53 117.15	12.70 155.12	9.53 117.15	-	15.09 183.42	20.62 247.83	12.70 155.12	50.01 564.81	26.19 311.17	32.54 381.53	38.10 411.49	44.45 508.11	56.01 564.81	-
22	559.00	4.78 66.57	5.54 70.06	6.35 86.54	9.53 129.13	12.70 171.09	9.53 129.13	-	-	22.23 294.25	12.70 171.09	53.98 672.26	28.58 373.83	34.93 451.42	41.28 527.02	47.63 600.63	53.98 672.26	-
24	610.00	5.54 84.16	6.35 96.37	6.35 94.53	9.53 141.12	14.27 209.64	9.53 141.12	-	17.48 255.41	24.61 355.26	12.70 187.06	59.54 808.22	30.96 422.08	38.89 547.71	46.02 640.03	52.37 720.15	59.54 808.22	-

Copper Tubes - ASTM B88M

Type A

Nominal Size Outside Diameter (mm)	Wall Thickness (mm)	Tolerance +/- Maximum Deviation at any Point (mm)	Weight (kg/m)
6	0.9	0.08	0.12
8	0.9	0.09	0.18
10	0.9	0.09	0.23
12	1.2	0.1	0.36
15	1.2	0.1	0.47
18	1.2	0.1	0.57
22	1.6	0.15	0.92
28	1.6	0.15	1.19
35	1.6	0.15	1.50
42	1.8	0.2	2.03
54	2.1	0.2	3.06
67	2.4	0.25	4.35
79	2.8	0.3	5.99
105	3.4	0.35	9.70
130	4.0	0.4	14.2
156	4.8	0.5	20.3
206	6.8	0.7	38.0
257	8.5	0.85	59.3
308	10.3	1	86.1

Type B

Nominal Size Outside Diameter (mm)	Wall Thickness (mm)	Tolerance +/- Maximum Deviation at any Point (mm)	Weight (kg/m)
6	0.7	0.07	0.10
8	0.8	0.08	0.16
10	0.8	0.08	0.21
12	0.9	0.09	0.28
15	1.0	0.1	0.39
18	1.0	0.1	0.48
22	1.1	0.1	0.65
28	1.2	0.1	0.90
35	1.4	0.15	1.32
42	1.5	0.15	1.71
54	1.7	0.15	2.50
67	2.0	0.15	3.65
79	2.3	0.2	4.95
105	2.8	0.25	8.04
130	3.1	0.3	11.0
156	3.5	0.3	15.0
206	5.0	0.35	28.2

Copper Tubes to BS (British Standard) 2871

(mm)	Outside Diameter (mm)	Table X Half hard light gauge tube		Table Y Half hard an annealed tube		Table Z Hard drawn thin wall tube	
		Thickness (mm)	Maximum Working Pressure (N/mm^2)	Thickness (mm)	Maximum Working Pressure (N/mm^2)	Thickness (mm)	Maximum Working Pressure (N/mm^2)
6	6	0.6	13.3	0.8	14.4	0.5	11.3
8	8	0.6	9.7	0.8	10.5	0.5	9.8
10	10	0.6	7.7	0.8	8.2	0.5	7.8
12	12	0.6	6.3	0.8	6.7	0.5	6.4
15	15	0.7	5.8	1	6.7	0.5	5
18	18	0.8	5.6	1	5.5	0.6	5
22	22	0.9	5.1	1.2	5.7	0.6	4.1
28	28	0.9	4	1.2	4.2	0.6	3.2
35	35	1.2	4.2	1.5	4.1	0.7	3
42	42	1.2	3.5	1.5	3.4	0.8	2.8
54	54	1.2	2.7	2	3.6	0.9	2.5
67	67	1.2	2	2	2.8	1	2
76.1	76.2	1.5	2.4	2	2.5	1.2	1.9
108	108.1	1.5	1.7	2.5	2.2	1.2	1.7
133	133.4	1.5	1.4			1.5	1.6
159	159.4	2	1.5			1.5	1.5

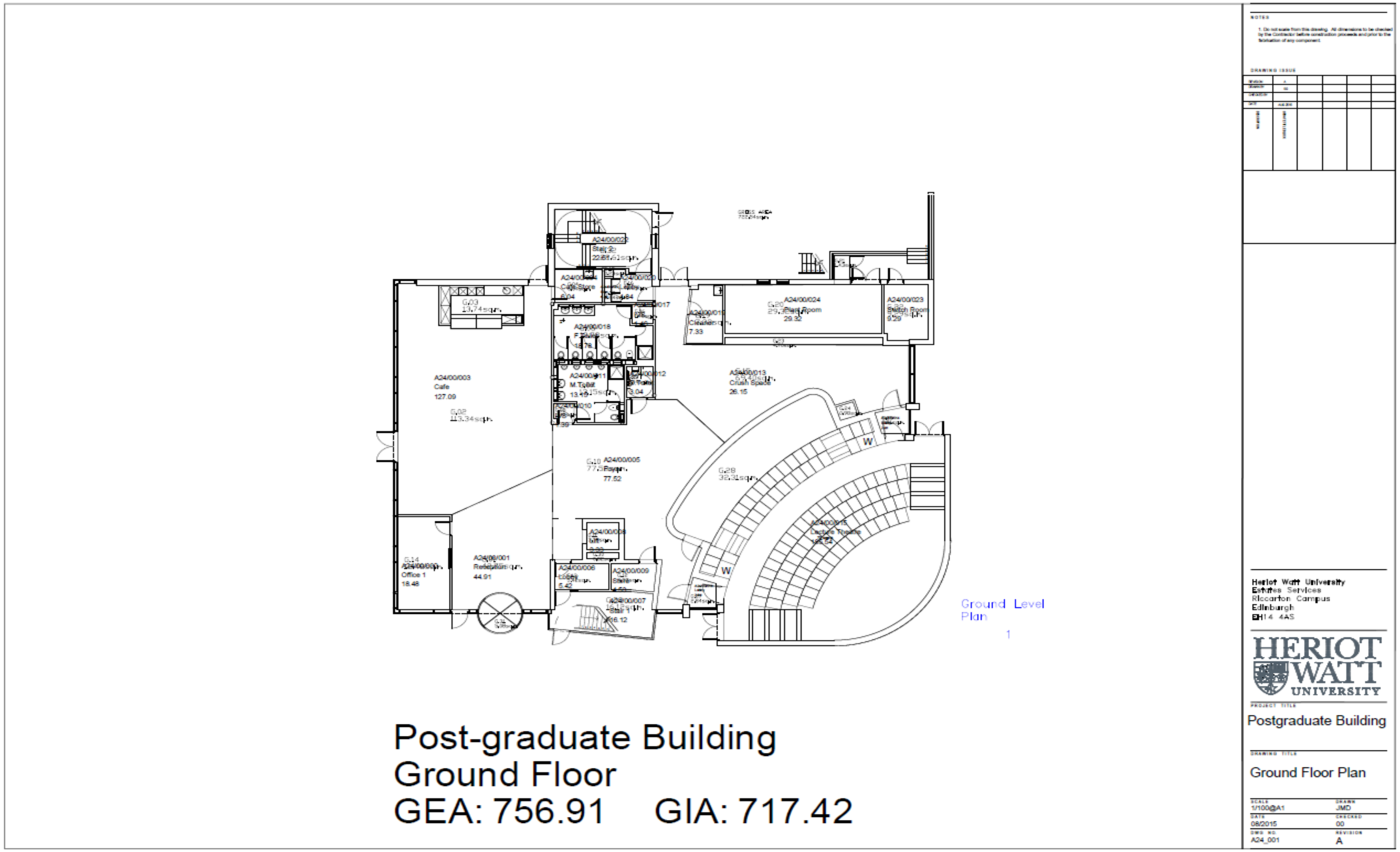
Stainless Steel Pipes - Dimensions and Weights ANSI/ASME 36.19

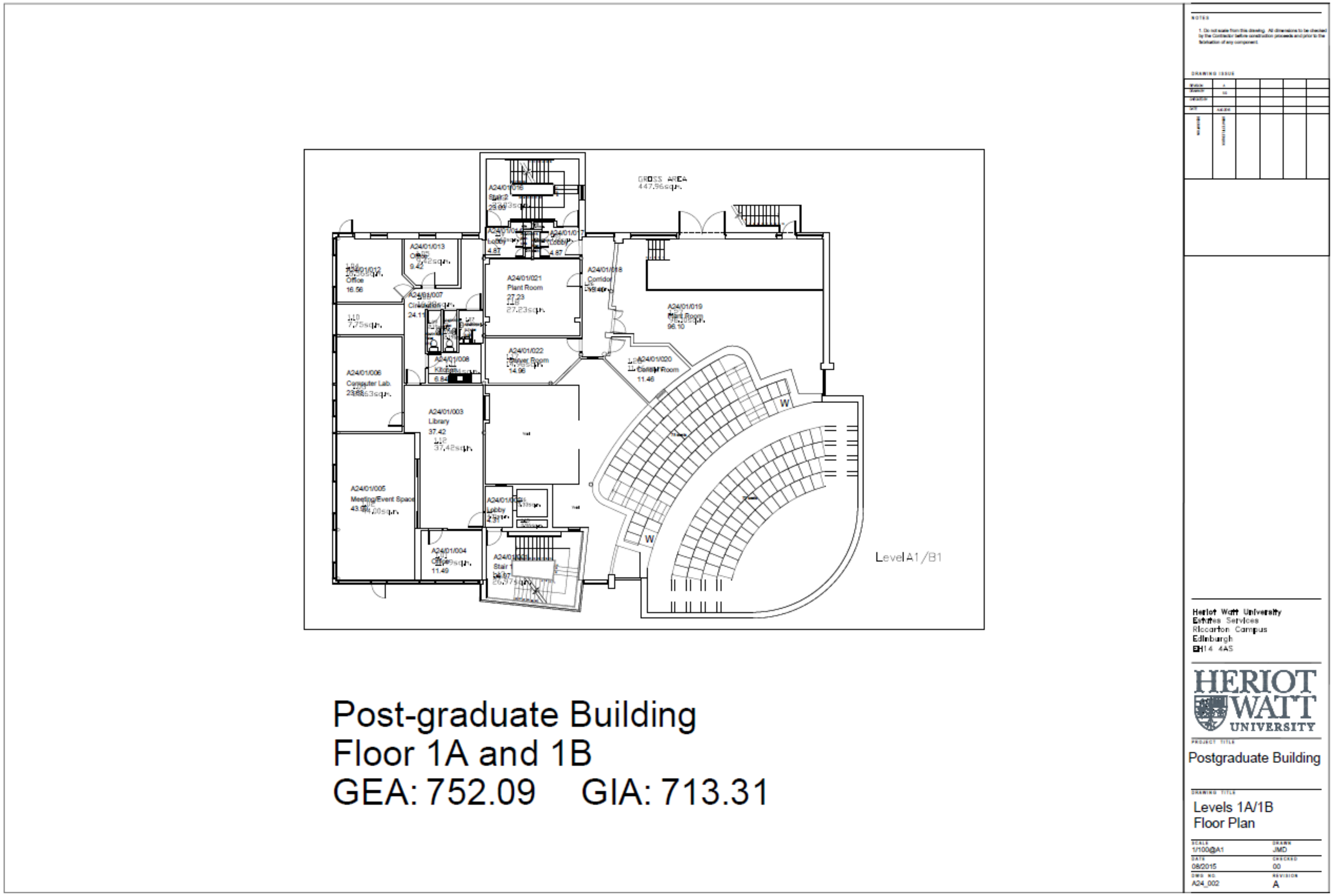
Nominal Pipe Size (inches)	Outside Diameter		Schedule									
			5S		10S		40S		80S		160S	
			Wall Thickness and Weight									
	(mm)	(inches)	mm (in)	kg/m	mm (in)	kg/m	mm (in)	kg/m	mm (in)	kg/m	mm (in)	kg/m
1/8	10.3	0.405	-	-	1.25 (0.049)	0.28	1.73 (0.068)	0.37	2.42 (0.095)	0.47	-	-
1/4	13.7	0.540	-	-	1.66 (0.065)	0.49	2.24 (0.088)	0.63	3.03 (0.119)	0.80	-	-
3/8	17.2	0.675	-	-	1.66 (0.065)	0.63	2.32 (0.091)	0.85	3.20 (0.126)	1.10	-	-
1/2	21.3	0.840	1.66 (0.065)	0.81	2.11 (0.083)	1.00	2.77 (0.109)	1.27	3.74 (0.147)	1.62	4.78	1.90
3/4	26.7	1.050	1.66 (0.065)	1.02	2.11 (0.083)	1.28	2.87 (0.113)	1.68	3.92 (0.154)	2.20	5.57	2.90
1	33.4	1.315	1.66 (0.065)	1.30	2.77 (0.109)	2.09	3.38 (0.133)	2.50	4.55 (0.179)	3.24	6.35	4.20
1 1/4	42.2	1.660	1.66 (0.065)	1.66	2.77 (0.109)	2.69	3.56 (0.140)	3.39	4.86 (0.191)	4.47	6.35	5.60
1 1/2	48.3	1.900	1.66 (0.065)	1.91	2.77 (0.109)	3.11	3.69 (0.145)	4.06	5.08 (0.200)	5.41	7.14	7.20
2	60.3	2.375	2.11 (0.065)	2.40	2.77 (0.109)	3.93	3.92 (0.154)	5.45	5.54 (0.218)	7.49	8.74	11.1
2 1/2	73.0	2.875	2.11 (0.083)	3.69	3.05 (0.120)	5.26	5.16 (0.203)	8.64	7.01 (0.276)	11.4	9.53	14.9
3	88.9	3.500	2.11 (0.083)	4.52	3.05 (0.120)	6.46	5.49 (0.216)	11.3	7.62 (0.300)	15.3	11.13	21.3
3 1/2	101.6	4.000	2.11 (0.083)	5.18	3.05 (0.120)	7.41	5.74 (0.226)	13.6	8.08 (0.318)	18.6	-	-

Dimensions for Metric PVC-U pipe Din 8061

Diameter mm			Wall Thickness mm		
Outside Diameter	Mean Outside Diameter		6 Bar	10 Bar	16 Bar
			Average Value	Average Value	Average Value
	min	max			
16	16	16.2	-	-	1.2
20	20	20.2	-	-	1.5
25	25	25.2	-	1.5	1.9
32	32	32.2	-	1.8	2.4
40	40	40.2	1.8	1.9	3.0
50	50	50.2	1.8	2.4	3.7
63	63	63.2	1.9	3.0	4.7
75	75	75.3	2.2	3.6	5.6
90	90	90.3	2.7	4.3	6.7
110	110	110.3	3.2	5.3	8.2
125	125	125.3	3.7	6.0	9.3
140	140	140.4	4.1	6.7	10.4
160	160	160.4	4.7	7.7	11.9
180	180	180.4	5.3	8.6	13.4
200	200	200.4	5.9	9.6	14.9
225	225	225.5	6.6	10.8	16.7
250	250	250.5	7.3	11.9	18.6
280	280	280.6	8.2	13.4	20.8
315	315	280.6	9.2	15.0	23.4

Appendix B: Floor plans of the case study buildins




GROSS AREA
447.96sq.m.
Level A1/B1
Post-graduate Building
Floor 1A and 1B
GEA: 752.09 GIA: 713.31
Heriot Watt University
Estates Services
Riccarton Campus
Edinburgh
EH14 4AS
HERIOT WATT UNIVERSITY
Postgraduate Building
Levels 1A/1B
Floor Plan
1/100@A1
JMD
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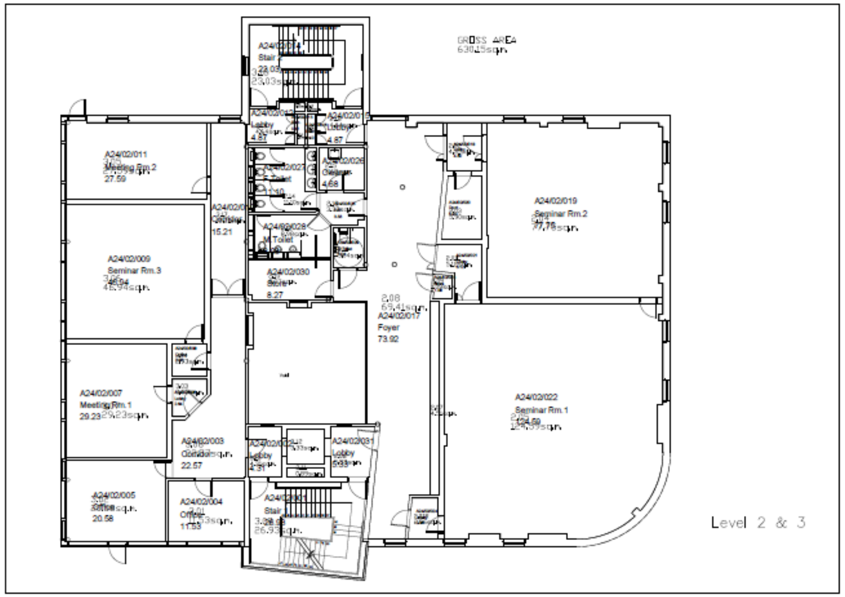
A24_002
A



Post-graduate Building
Floor 2 & 3
GEA: 704.49 GIA: 665.56

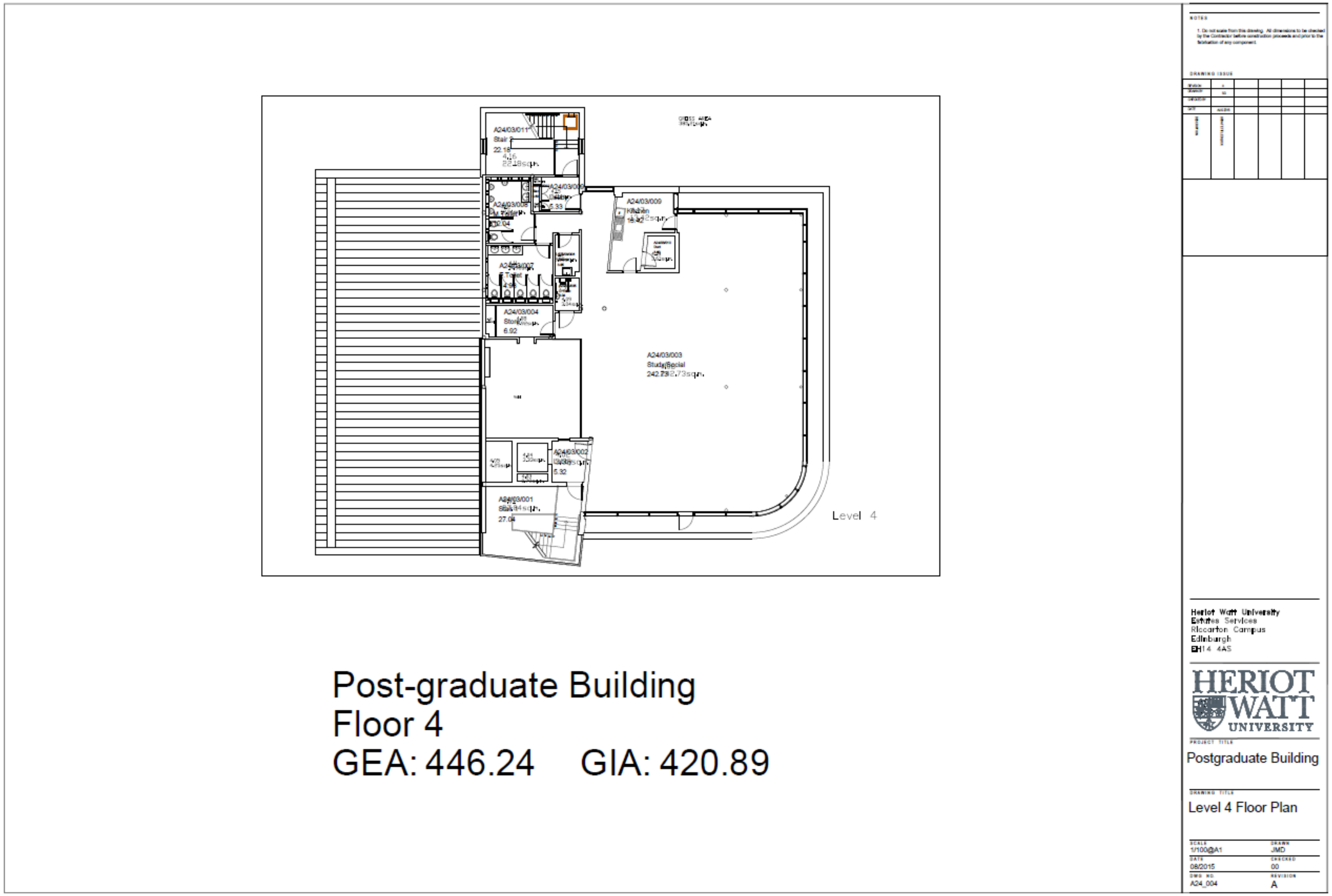
Heriot Watt University
Estates Services
Riccarton Campus
Edinburgh
EH14 4AS

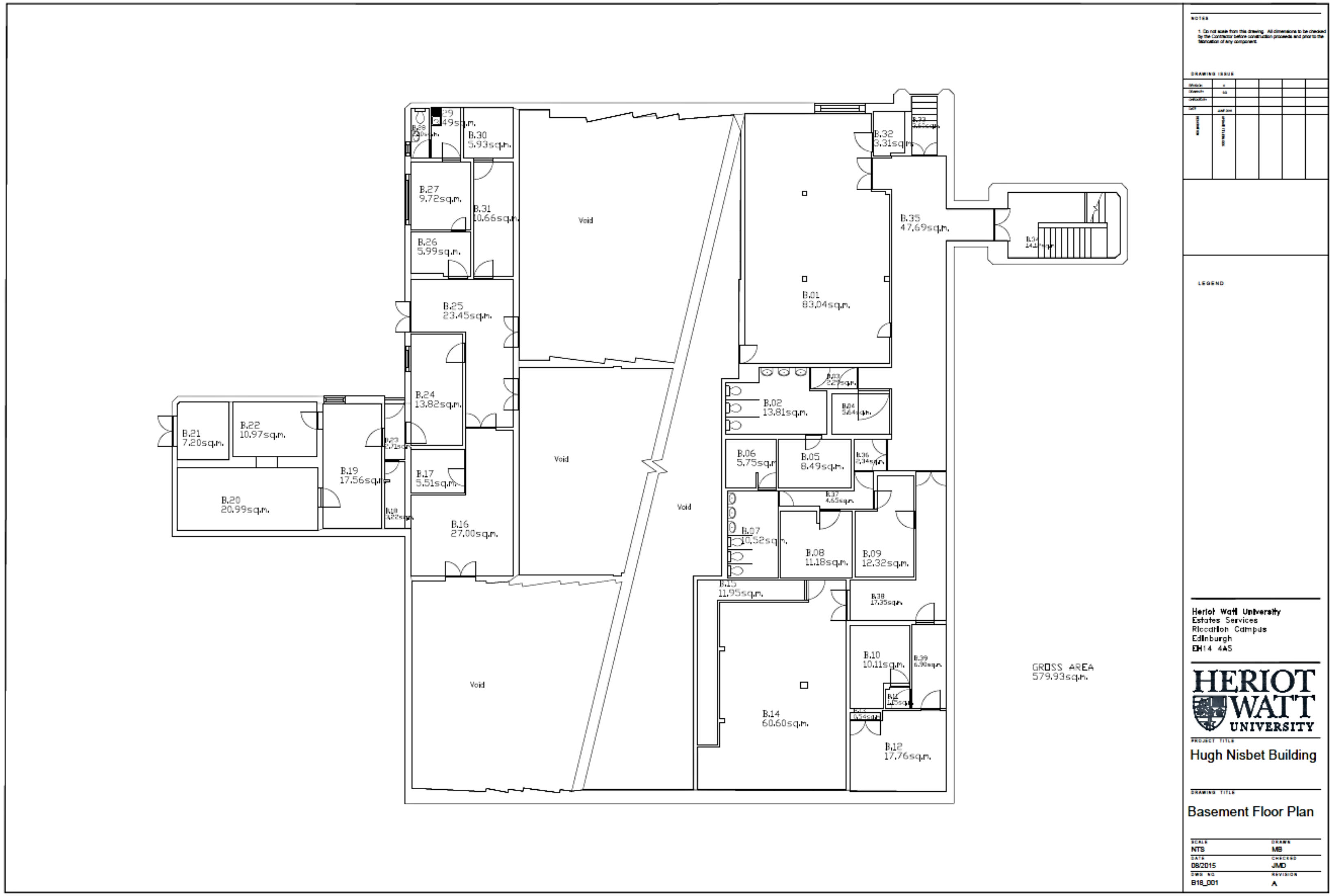
HERIOT WATT UNIVERSITY

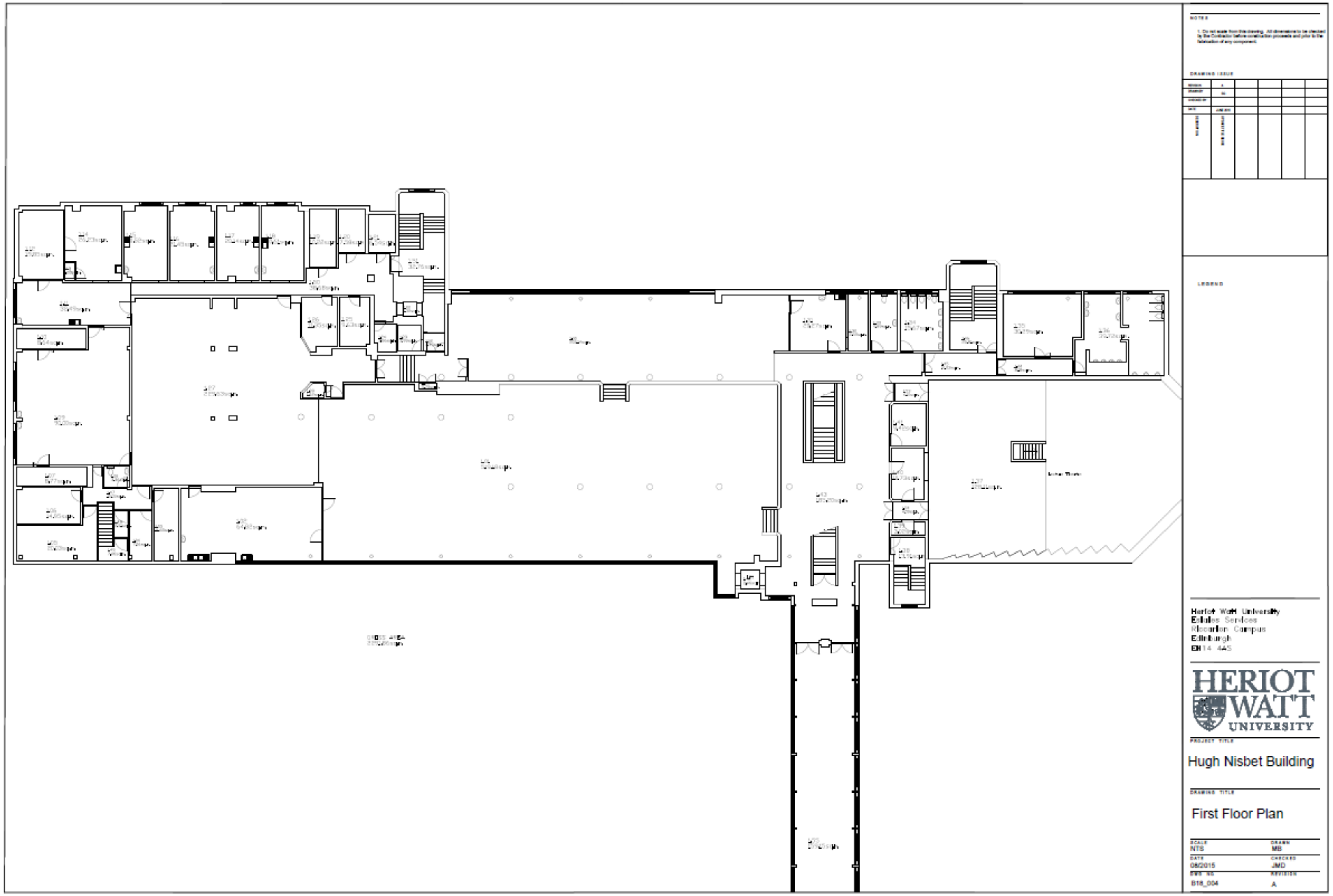
PROJECT TITLE
Postgraduate Building

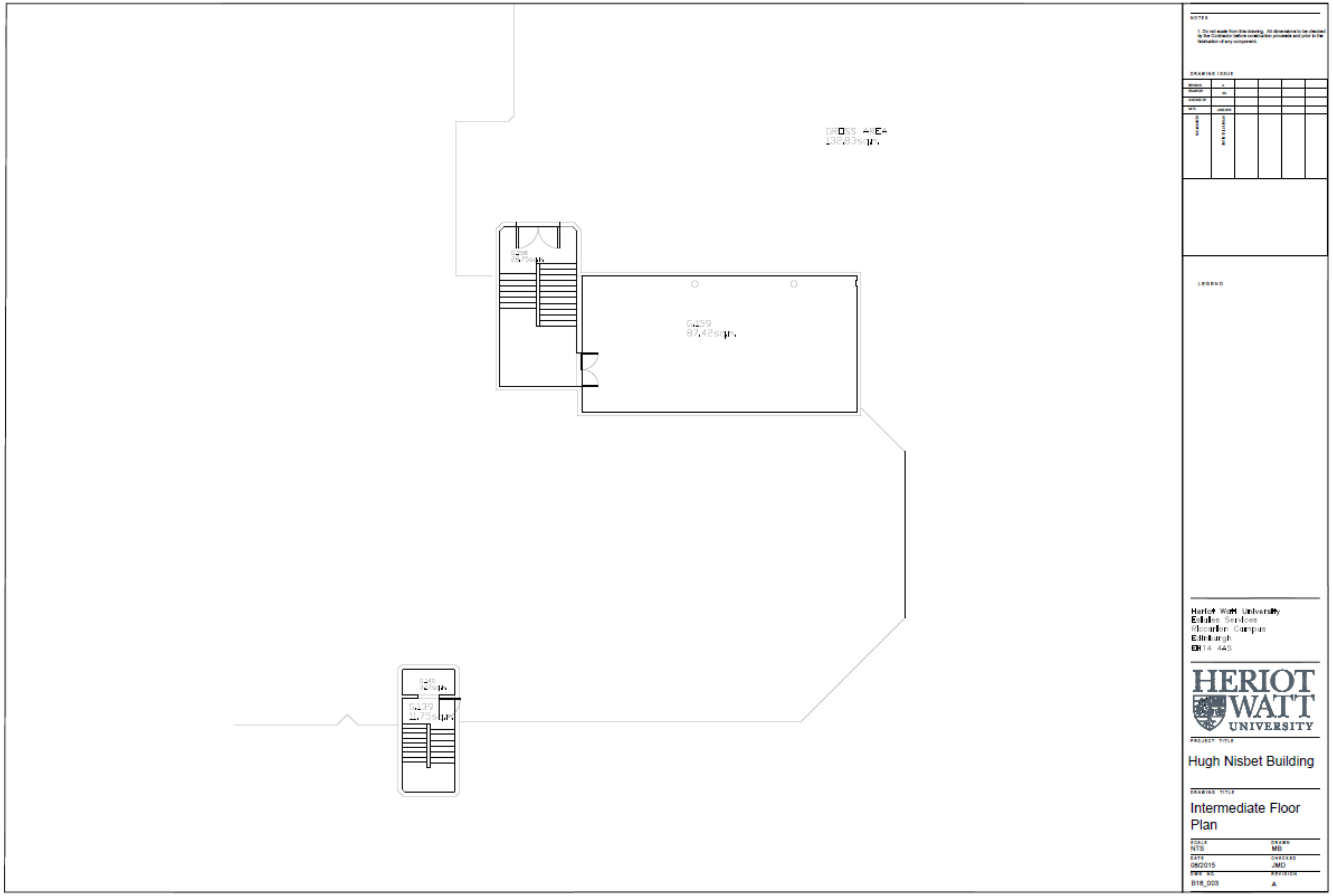
DRAWING TITLE
Levels 2 and 3
Floor Plan

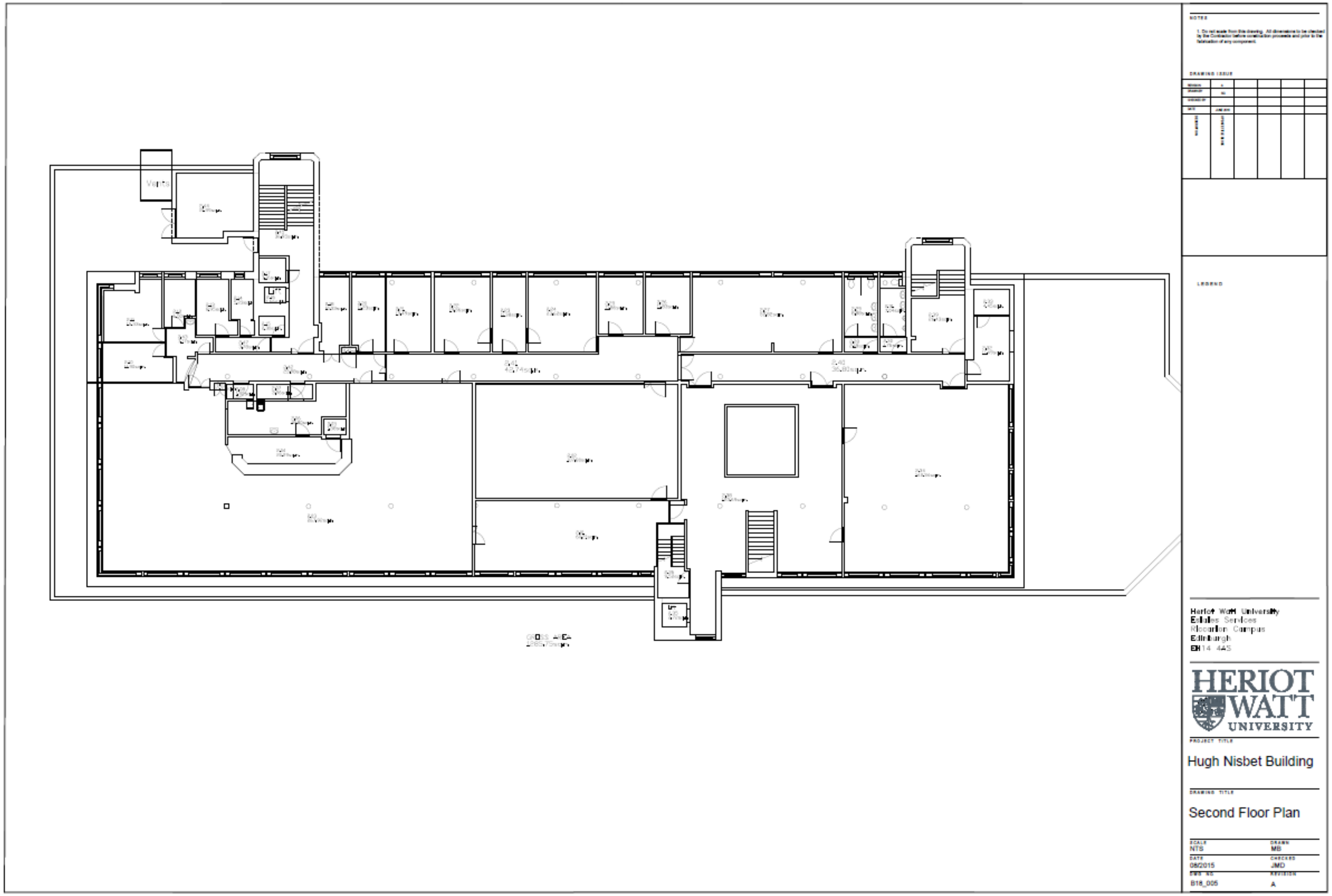
SCALE 1/100@A1	DRAWN JMD
DATE 08/2015	CHECKED 00
DWG NO A24_003	REVISION A

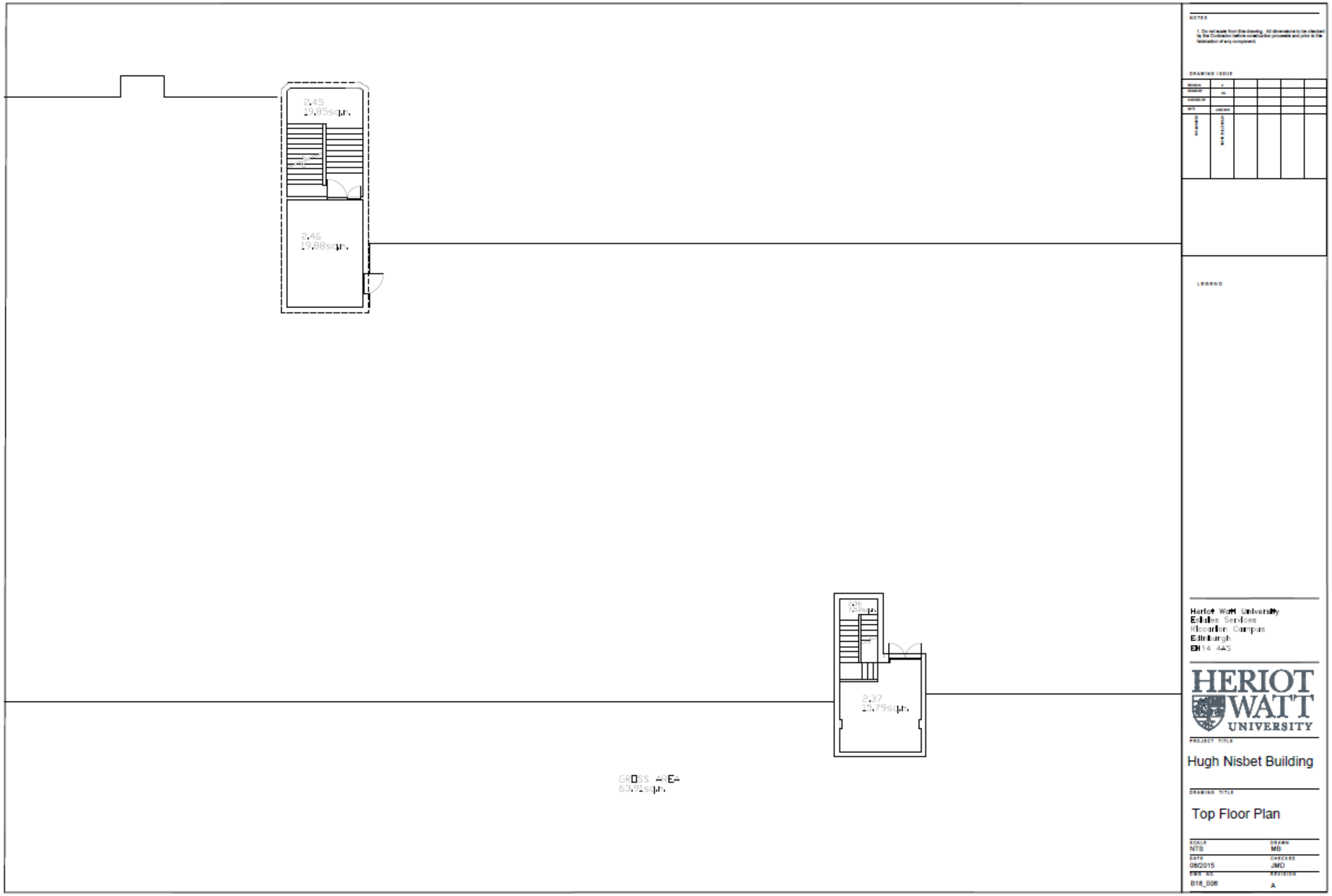

Level 4
Post-graduate Building
Floor 4
GEA: 446.24 GIA: 420.89
Heriot Watt University
Estates Services
Riccarton Campus
Edinburgh
EH14 4AS
HERIOT WATT UNIVERSITY
Postgraduate Building
Level 4 Floor Plan
1/100@A1
JMD
08/2015
00
A24_004
A


B.30
5.93sq.m.
B.27
9.72sq.m.
B.31
10.66sq.m.
B.26
5.99sq.m.
B.25
23.45sq.m.
B.24
13.82sq.m.
B.21
7.20sq.m.
B.22
10.97sq.m.
B.19
17.56sq.m.
B.20
20.99sq.m.
B.17
5.51sq.m.
B.16
27.00sq.m.
Void
Void
Void
Void
B.32
3.31sq.m.
B.35
47.69sq.m.
B.01
83.04sq.m.
B.02
13.81sq.m.
B.06
5.75sq.m.
B.05
8.49sq.m.
B.07
10.52sq.m.
B.08
11.18sq.m.
B.09
12.32sq.m.
B.15
11.95sq.m.
B.10
10.11sq.m.
B.14
60.60sq.m.
B.12
17.76sq.m.
GROSS AREA
579.93sq.m.
Heriot Watt University
Estates Services
Riccarton Campus
Edinburgh
EH14 4AS
HERIOT WATT UNIVERSITY
Hugh Nisbet Building
Basement Floor Plan
NTS
MB
08/2015
JMD
B18_001
A


Heriot Watt University
Estates Services
Riccarton Campus
Edinburgh
EH14 4AS
PROJECT TITLE
Hugh Nisbet Building
DRAWING TITLE
First Floor Plan
SCALE
NTS
DRAWN
MB
DATE
08/2015
CHECKED
JMD
DWG NO
B18_004
REVISION
A


NOTES
1. Do not scale from this drawing. All dimensions to be checked by the Contractor before construction proceeds and prior to the fabrication of any component.
DRAWING ISSUE
LEGEND
GROSS AREA
132.83sq.m.
G.159
87.42sq.m.
Heriot Watt University
Estates Services
Riccarton Campus
Edinburgh
EH14 4AS
HERIOT WATT UNIVERSITY
PROJECT TITLE
Hugh Nisbet Building
DRAWING TITLE
Intermediate Floor Plan
SCALE
NTS
DRAWN
MB
DATE
08/2015
CHECKED
JMD
DWG NO
B18_003
REVISION
A


Vents
Heriot Watt University
Estates Services
Riccarton Campus
Edinburgh
EH14 4AS
HERIOT WATT UNIVERSITY
Hugh Nisbet Building
Second Floor Plan
NTS
MB
08/2015
JMD
B18_005
A


2.45
19.85sq.m.
2.46
19.88sq.m.
2.37
15.79sq.m.
GROSS AREA
63.91sq.m.
LEGEND
Heriot Watt University
Estates Services
Riccarton Campus
Edinburgh
EH14 4AS
PROJECT TITLE
Hugh Nisbet Building
DRAWING TITLE
Top Floor Plan
SCALE
NTS
DRAWN
MB
DATE
08/2015
CHECKED
JMD
DWG NO
B18_008
REVISION
A

Appendix C: Calculation of LUs and design flow rate for the case study buildings

Estates building

No.	Draw-off point	Loading Unit																					
		BS 6700					BS 8558					BS EN 806					IoP						
		LU	No.	Cold	Hot	Total	LU	No	Cold	Hot	Total	LU	No.	Cold	Hot	Total	Low	Mid	No	Cold	Hot	Total	High
1	**WC**	2	9	18		18	2	9	18		18	1	9	9		9	1	2	9	18		18	5
2	**Bidet**	2		0	0	0	2		0	0	0	1		0	0	0	1	1		0	0	0	-
3	**Wash basin**																						
	½ – DN 15 sep taps **1.5 -3**	3	8	24	24	48	3	3	9	9	18	1	8	8	8	16	1	2	3	6	6	12	4
	2 x 8mm mix. tap						3	5	15		15			0		0	1	1	5	5	5	10	2
4	**Urinal**	0	2	0		0	0	2	0		0	3	2	6		6		1	2	2		2	
5	**Shower**	3	1	3	3	6	3	1	3		3	2	1	2		2	2	3	1	3	0	3	6
6	**Bath**																						
	Domestic											4		0	0	0							
	Non-Domestic											8	0	0	0	0							
	15mm sep/mix/tap																4	8		0	0	0	16
	¾ – DN 20	10		0	0	0	10		0		0						-	11		0	0	0	-
	1 – DN 25	22		0	0	0	22		0		0												
7	**Sink**					0																	
	½ – DN 15 tap	3	2	6	6	12	3	0	0	0	0												
	¾ – DN 20 tap	5	3	15	15	30	5	3	15	15	30												
	½ – DN 15 Mixer						3	2	6		6												
	¾ – DN 20 Mixer						5		0		0												
	Domestic											2	3	6	6	12							
	Non-Domestic											8	2	16	16	32							
	Sink, 15mm sep/mix tap																2	5	5	25	25	50	10
	Sink, 20mm sep/mix tap																-	7		0	0	0	-
8	**Clothes washing amchine**																						
	Domestic	3		0		0	3		0		0	2		0		0							
	Domestic				ds												2	2		0		0	-
9	**Dishwasher machine**																						
	Domestic	3	1	3		3	3	1	3		3	2	1	2		2							
	Domestic																2	2	1	2		2	-
10	**Others**																						
	Bucket sink, 15mm **taps**	3	1	3	3	6	3	1	3	3	6	2	1	2	2	4	-	1	1	1	1	2	-
	15mm **Mixer**						3		0		0	8	0	0	0	0							
	Hand Spray, 15mm																-	1		0	0	0	-
	Slop Hopper																						
	cistern only																-	1		0	0	0	-
	cistern/taps																-	3		0	0	0	-
	Total		27			123		27			99		27			83			27			99	
	Flow rates *l/s*					1.42					1.21					1.62						1.22	

Postgraduate Centre

No.	Draw-off point	Loading Unit																					
		BS 6700					BS 8558					BS EN 806					IoP						
		LU	No.	Cold	Hot	Total	LU	No	Cold	Hot	Total	LU	No.	Cold	Hot	Total	Low	Mid	No	Cold	Hot	Total	High
1	**WC**	2	24	48		48	2	24	48		48	1	24	24		24	1	2	24	48		48	5
2	**Bidet**			0	0	0	2		0	0	0	1	2	2	2	4	1	1	2	2	2	4	-
3	**Wash basin**																						
	½ – DN 15 sep taps 1.5 -3	3	22	66	66	132	3	18	54	54	108	1	22	22	22	44	1	2	18	36	36	72	4
	2 x 8mm mix. tap						3	4	12		12			0		0	1	1	4	4	4	8	2
4	**Urinal**	2		0		0	2		0		0	3	10	30		30		1	10	10		10	
5	**Shower**	3	2	6	6	12	3	2	6		6	2	2	4		4	2	3	2	6	6	12	6
6	**Bath**																						
	Domestic											4		0	0	0							
	Non-Domestic											8		0	0	0							
	15mm sep/mix/tap																4	8		0	0	0	16
	¾ – DN 20	10		0	0	0	10		0		0						-	11		0	0	0	-
	1 – DN 25	22		0	0	0	22		0		0												
7	**Sink**					0																	
	½ – DN 15 tap	3	4	12	12	24	3	4	12	12	24												
	¾ – DN 20 tap	5		0	0	0	5		0	0	0												
	½ – DN 15 Mixer						3		0		0												
	¾ – DN 20 Mixer						5		0		0												
	Domestic											2		0	0	0							
	Non-Domestic											8	4	32	32	64							
	Sink, 15mm sep/mix tap																2	5	4	20	20	40	10
	Sink, 20mm sep/mix tap																-	7		0	0	0	-
8	**Clothes washing amchine**																						
	Domestic	3	1	3		3	3	1	3		3	2	1	2		2							
	Domestic				ds												2	2	1	2		2	-
9	**Dishwasher machine**																						
	Domestic	3		0		0	3		0		0	2		0		0							
	Domestic																2	2		0		0	-
10	**Others**																						
	Bucket sink, 15mm **taps**	3	4	12	12	24	3	4	12	12	24	8	4	32	32	64	-	1	4	4	4	8	-
	15mm **Mixer**						3		0		0			0		0							
	Hand Spray, 15mm																-	1		0	0	0	-
	Slop Hopper																						
	cistern only																-	1		0	0	0	-
	cistern/taps																-	3		0	0	0	-
	Total		57			243		57			225		69			236			69			204	
	Flow rates *l/s*					2.50					2.29					1.68						2.40	

Hugh Nisbet building

No.	Draw-off point	Loading Unit																					
		BS 6700					BS 8558					BS EN 806					IoP						
		LU	No.	Cold	Hot	Total	LU	No	Cold	Hot	Total	LU	No.	Cold	Hot	Total	Low	Mid	No	Cold	Hot	Total	High
1	**WC**	2	45	90		90	2	45	90		90	1	45	45		45	1	2	45	90		90	5
2	**Bidet**	2		0	0	0	2		0	0	0	1		0	0	0	1	1		0	0	0	-
3	**Wash basin**																						
	½ – DN 15 sep taps 1.5 -3	3	72	216	216	432	3	28	84	84	168	1	72	72	72	144	1	2	28	56	56	112	4
	2 x 8mm mix. tap						3	44	132		132			0		0	1	1	44	44	44	88	2
4	**Urinal**	2	0	0		0	2	0	0		0	3	18	54		54		1	18	18		18	
5	**Shower**	3		0	0	0	3		0		0	2		0		0	2	3		0	0	0	6
6	**Bath**																						
	Domestic											4		0	0	0							
	Non-Domestic											8		0	0	0							
	15mm sep/mix/tap																4	8		0	0	0	16
	¾ – DN 20	10		0	0	0	10		0		0						-	11		0	0	0	-
	1 – DN 25	22		0	0	0	22		0		0												
7	**Sink**					0																	
	½ – DN 15 tap	3	19	57	57	114	3	19	57	57	114												
	¾ – DN 20 tap	5		0	0	0	5		0	0	0												
	½ – DN 15 Mixer						3		0		0												
	¾ – DN 20 Mixer						5		0		0												
	Domestic											2		0	0	0							
	Non-Domestic											8	19	152	152	304							
	Sink, 15mm sep/mix tap																2	5	19	95	95	190	10
	Sink, 20mm sep/mix tap																-	7		0	0	0	-
8	**Clothes washing amchine**																						
	Domestic	3		0		0	3		0		0	2		0		0							
	Domestic				ds												2	2		0		0	-
9	**Dishwasher machine**																						
	Domestic	3	6	18		18	3	6	18		18	2	6	12		12							
	Domestic																2	2	6	12		12	-
10	**Others**																						
	Bucket sink, 15mm taps	3	5	15	15	30	3	5	15	15	30	8	5	40	40	80	-	1	5	5	5	10	-
	15mm **Mixer**						3		0		0			0		0							
	Hand Spray, 15mm																-	1		0	0	0	-
	Slop Hopper																						
	cistern only																-	1		0	0	0	-
	cistern/taps																-	3		0	0	0	-
	Total		147			684		147			552		165			639			165			520	
	Flow rates ***l/s***					5.00					4.41					2.68						4.28	