

Dynamic Sewer Modelling
**How using water saving appliances affects nutrient
concentrations in wastewater**

CE30122

By: Dean Hodgson

Dept. Chemical Engineering University of Bath

Bath, BA2 7AY

Supervisor: Prof Jan Hofman

Submitted: 27/04/2021

**Water Innovation
& Research
Centre**



UNIVERSITY OF
BATH

Authorship Declaration

I certify that I have read and understood the entry in the Programme Handbook for the Department of Chemical Engineering on Cheating and Plagiarism and that all material in this report is my own work, except where I have indicated with appropriate references or acknowledgements. I agree that, in line with Regulation 15.3(e), if requested I will submit an electronic copy of this work for submission to a Plagiarism Detection Service for quality assurance purposes.

Name: Dean Hodgson

Signature: D.Hodgson

Date: 27/04/2021

Abstract

Growing global population has led to increasing levels of water scarcity around the world. Governments and companies are developing strategies to try and reduce household water usage, with one of these main strategies being to implement water saving appliances into households to reduce water consumption, from dual-flush toilets to aerated taps. With reduced water consumption in houses the inflow into sewer systems will drastically reduce and wastewater concentrations will increase. Current piping sizes in sewer networks may be very oversized for the reduced flow from households. Separated sewer networks also reduce the flow in foul sewer systems and increase concentration by removing the stormwater factor that may have existed in previous combined sewer networks. The work presented here shows a stochastic sewer model which can predict hydraulic flow in sewer networks as well as nutrient concentrations. The stochastic model was calibrated to the UK population using data on household occupancy, time use information and appliance specific consumption information. The model works on the integration of water discharge patterns from SIMDEUM and SIMDEUM WW with the sewer modelling software SWMM. The sewer network for which the model was simulated was a new housing development in Brabazon, Bristol, UK and was designed as a separated sewer network where the only inflows are from residential houses. 3 water saving appliances were explored in this research, including water saving toilets, shower heads and waterless washing machines. The flowrate of the wastewater and the concentrations of Phosphorus, Nitrogen, COD and SS were all simulated to observe the effects of using water saving appliances. It was found that through the use of a separated sewer network, concentrations in the wastewater were much higher than for combined sewer networks and using water saving appliances decreased the flow into the network and increased the wastewater concentrations further. The case studied area was simulated with diurnal patterns over a 5-day week period and the flowrate of wastewater was reduced by 18.2% over the morning peak water use periods, which resulted in the average concentrations of Phosphorous, Nitrogen, COD and SS increasing by 27.9%, 3.4%, 13.6% and 9.3% respectively. Possible development of this model into the future was also discussed at the end of this report.

Table of Contents

1. Introduction.....	1
2. Literature Review.....	3
2.1- Background.....	3
2.2- Urban Sewer Systems.....	4
2.2.1- Urban Networks and the Water Cycle.....	4
2.2.2- Wastewater- The Nutrients.....	5
2.2.3- Wastewater Treatment- Nutrient Recovery.....	5
2.3- Future of urban sewer systems.....	6
2.3.1- Sustainable development of sewage systems.....	6
2.3.2- Water saving appliances.....	7
2.3.3- Impact of water saving appliances on nutrient recovery.....	8
2.4- Modelling sewer flows.....	9
2.4.1- Sewer modelling software- SWMM.....	9
2.4.2- Deterministic and Stochastic modelling.....	11
2.5- The future of water use.....	12
2.6- Concluding Remarks.....	13
2.7 Aims and Objectives.....	13
3. Case Study.....	14
3.1- Site Description.....	14
3.2- Sewer Network Description.....	17
4. Methodology.....	18
4.1- Modelling approach.....	18
5. Data and model calibration.....	21
5.1- Data Collection.....	21
5.2- SIMDEUM.....	26
5.3- SIMDEUM WW.....	27
5.4- SWMM.....	28
6. Results and discussion.....	29
6.1- Calibration Results.....	29
6.2- Simulation Results- Flow Rate.....	31
6.3- Simulation Results- Nutrient Concentration.....	34
7. Future work.....	39
8. Conclusion.....	40
Acknowledgements.....	41
References.....	42
Appendix.....	46

1. Introduction

The world is constantly moving towards a more sustainable future. According to the UN (2015) the domestic sector accounts for 10% of total water use in the world, and by 2050 more than two-thirds of the global population will be living in cities. As water becomes an increasingly scarce commodity it is important that technology improves in households in order to help reduce water consumption and conserve water. With cities continuing to grow it is also important that effective sewer networks are designed, and existing networks are expanded to aid towards a sustainable future. One of the main differences between old and new sewer networks is the change from combined sewer networks to separated sewer networks, where household wastewater and stormwater are not collected together. In combined sewer systems, if the capacity is exceeded, combined sewer overflows (CSOs) can occur, where the excess wastewater is discharged into surface water, which can cause major ecological damage if events such as eutrophication occur due to the high levels of phosphorous and nitrogen in the wastewater. Separated systems therefore reduce the chances of environmental damage caused by CSOs whilst also reducing dilution of nutrients in the wastewater. In the wastewater only sewer system, the overall flow will be reduced as the only inputs into the system will be from connected households, and as water consumption is reduced due to water saving methods, the wastewater concentrations will increase. Increased sewage concentrations could lead to the potential of more effective water treatment as well as nutrient recovery.

The purpose of this work is therefore to develop a model to predict and understand how using water saving household appliances will affect diurnal patterns of wastewater flows and nutrient concentrations for a residential area described further in Section 3. A stochastic model will be developed by calibrating data using the UK population, producing household discharge patterns in SIMDEUM and simulating in a hydraulic modelling software called Storm Water Management Model (SWMM). The model developed will allow for the testing of future water saving appliances and the effects on the sewer flow and nutrient concentrations will be able to be observed.

Most previously developed sewer models have been deterministic, which models gross solid movement in sewers. This work attempts to develop a stochastic model to better display the

varying flowrates and concentrations in the sewer networks following diurnal patterns of households.

This work develops UK calibrated data and .spg files using the Watershare Water-Use Info Tool that is inputted into SIMDEUM to generate stochastic water use profiles based on household data (gender, age etc.), water use behaviour (shower durations, toilet flush frequencies) and typical appliance flows (Blokke et al., 2010). The discharge patterns produced are then linked with a relatively new code, SIMDEUM WW, which assigns appliance specific nutrient discharge concentrations on a per use basis to the stochastic demand profiles and produces stochastic wastewater discharge profiles. Another feature of the SIMDEUM WW code is that the discharge profiles differ slightly from the demand profiles due to specifics of certain appliances, for example, a toilet discharges more quickly than it fills whilst a washing machine has a different discharge profile than its demand profile. So far there has been very little validation for wastewater patterns. The discharge patterns for flow and nutrient concentrations are then linked with households in the case studied area using SWMM.

The work in this paper begins with a literature review (Section 2) which gives an overview of urban water cycles, sewer networks, nutrient recovery and modelling techniques as well as the aims of this research; a case study (Section 3) which describes in more detail the area for which the sewer network is being developed and modelled for; a methodology (Section 4) which describes the steps taken to carry out this research; model data calibration (Section 5); results and discussion (Section 6) which displays and explores the findings of the simulations; future work (Section 7) where ideas are explored of what could change in this research if developed further in the future and finally a conclusion (Section 8) which describes the main findings of this research. Acknowledgements, references and appendices can be found at the end of this report.

2. Literature Review

2.1- Background

Over the last few decades there has been an increasing demand for water, which has led to water scarcity and fears of the pressure on the planet's water resources. Water scarcity has become more of a problem over recent times due to a rapidly rising global population, socio-economic developments, and changes in the human diet towards animal products (Liu et al., 2017; Falkenmark et al., 1989). Throughout the world there are countries struggling due to the effects of water scarcity. Between 1995 and 2025 the areas of the world affected by severe water stress is expected to expand by over 2 million km². Globally, competition for scarce water resources will increase between households, industry, and agriculture (Alcamo et al., 2000). According to the *Global Risks 2015* report by the World Economic Forum, water crises was listed as the number 1 global risk in terms of impact (World Economic Forum, 2015). Over the past couple of years, the impact of infectious diseases has taken the top spot due to the impacts of COVID-19, however, all over the world there is still a water crisis having a huge negative impact (World Economic Forum, 2021).

Through the treatment of wastewater there is a potential to recover many useful nutrients and energy which could release the pressure on the world's non-renewable resources. At the current rate of mining, phosphorus, which is mostly used for fertilisers in agriculture, could be completely drained by the end of this century (Wageningen, 2021). By removing phosphorus from wastewater and using phosphorus recovery technologies in water treatment, over 20 % of the global requirement could be met (Carrillo et al., 2020). The issues come due to the fact that wastewater from the current sewer networks is extremely diluted, so nutrient concentrations are low which reduces the efficiency of nutrient recovery. By separating sewer networks between storm water and residential foul water, and by using water saving appliances in houses, the amount of water and therefore dilution in the sewer networks can be reduced, which would increase the efficiency of water treatment (Verstraete and Vlaeminck, 2011).

The reduction of water consumption and discharge from residential houses in urban areas has not only been gaining interest for sustainability and water scarcity reasons, but also due to the fact that urban areas are constantly expanding. It would be best to connect new systems to the existing networks without building entire new networks, and the pressure on these existing networks can be reduced by decreasing the wastewater flow into the system.

2.2- Urban Sewer Systems

2.2.1- Urban Networks and the Water Cycle

Urban sewer networks were originally developed to transport waste and stormwater away from urban areas due to the fear and hygiene implications of using human waste. Sewer systems were originally designed as combined sewer networks. Figure 2.2-1, provided by NYC.gov, 2021, shows the combined sewer network that still exists in most of the UK urban areas.

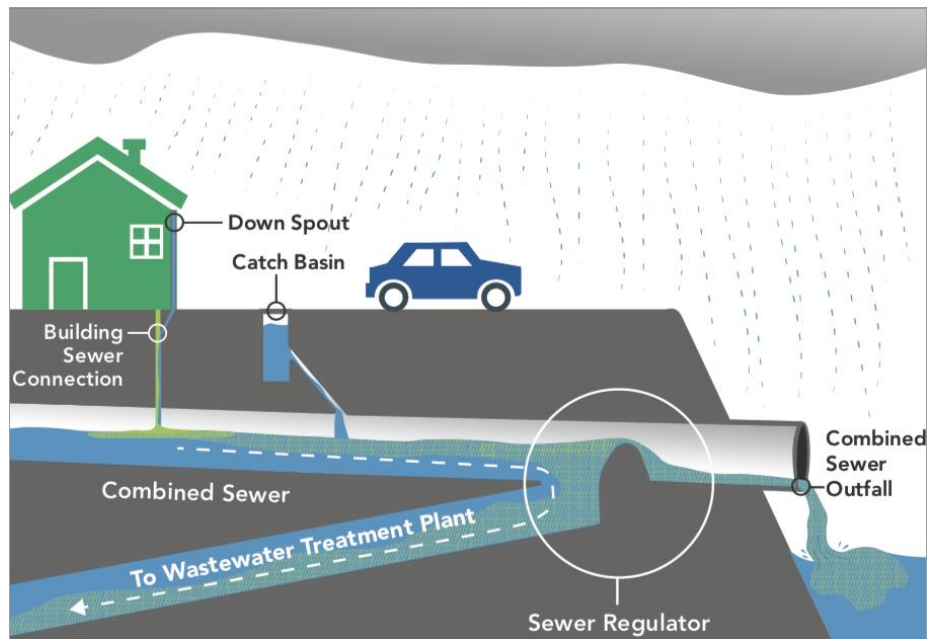


Figure 2.2-1- A display of a combined urban sewer network.

In a combined sewer a single pipe is used to carry both the foul water from households and the stormwater runoff from the urban area. This water is normally then taken to a wastewater treatment plant where nutrients can be extracted, and the treated water can be discharged into a local water source. The combined networks are designed to facilitate peak rainfall volumes which means in general and dry weather the network pipes are oversized. In a heavy rainstorm, combined sewers receive flows much higher than normal, which can lead to a mix of stormwater and untreated wastewater overflowing into other water sources, leading to damaged ecosystems. This is called a combined sewer overflow (CSO) and they are concerning due to the negative impacts on local water bodies and ecosystems.

As of recent times and into the future, sewer networks are being designed as separated sewer systems, where there are two different pipes for stormwater and wastewater. However, a lot of the existing sewer networks are not designed in this way and as urban areas expand and connections are made to the existing networks, water consumption must be reduced to alleviate the pressure on these existing networks.

2.2.2- Wastewater- The Nutrients

Wastewater quality is affected by the contaminants that human and domestic activities discharge into it. One of the largest contributors of pollutants in wastewater in residential areas is human excreta. Adults on average produce 200-300 g of faeces per day, contributing 25-30 g/hd.d BOD, and 1-3 kg of urine per day, contributing 10 g/hd.d BOD which overall accounts for 60% of the organic compounds found in wastewater (Feachem et al., 1981). Other main sources of pollutants into wastewater from households are gross solids from toilets, such as toilet paper; urea contributes a large portion of nitrogen; undigested foods contribute fats; washing/laundry contribute the majority of the phosphorus load (although this is decreasing due to new legislations imposing restrictions on detergents (Morse et al., 1993)).

2.2.3- Wastewater Treatment- Nutrient Recovery

Wastewater from domestic dwellings contains a host of nutrients that if extracted could be useful in many applications. For example, nitrogen and phosphorus, could be used in the production of fertilisers for agriculture. These nutrients may also be removed from the wastewater for other reasons; it is necessary to remove nitrogen and phosphorus to reduce the potential of eutrophication in water sources that the water may be expelled into (Bunce et al., 2018) as well as the build-up of struvite in mechanical systems (Haddaway, 2015). Nutrient recovery reduces the likelihood of these problems while also improving water quality and meeting government discharge limits. Another advantage of nutrient recovery is it offers the potential revenue stream by providing phosphorus, a growingly scarce commodity, to agricultural businesses (Haddaway, 2015).

The most common wastewater treatment process in the western world is the Conventional Activated Sludge (CAS) system. The CAS system is an efficient method of removing organic matter from wastewater. However, in recent times new regulations on nutrients have become more stringent. This has made the CAS process an extremely energy intensive process due to the need for new infrastructure and the added chemical and energy requirements (Verstraete & Vlaeminck, 2011).

As the main objective of wastewater treatment is organics removal, anaerobic digestion is one of the key process. The problem comes due to the fact that the concentration of organics in household wastewater tends to be extremely low. Therefore, the wastewater needs to be preconcentrated to aid in organics and nutrient removal. This can either be done with a concentrator at the treatment plant, or further upstream, such as in homes, where using water

saving appliances will reduce dilution in wastewater. Figure 2.2-2 shows a possible treatment plant for the extraction of nutrients from sewage. For the removal of other nutrients such as nitrogen other steps in the process may be needed, such as denitrification (Mulder, 2014).

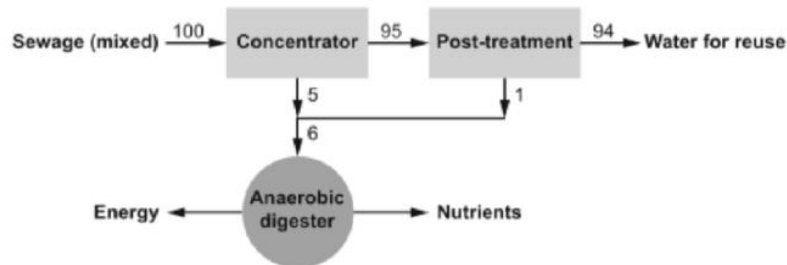


Figure 2.2-2-Example wastewater treatment plant for nutrient recovery. Numbers show relative water flow rates (Larsen et al., 2013).

2.3- Future of urban sewer systems

2.3.1- Sustainable development of sewage systems

Sustainable development was defined by Bruntland as, ‘that which meets the needs and aspirations of the present generation without compromising the ability of future generations to meet their own needs’. At the UN Earth Summit governments were called upon to produce plans for sustainable development, based on existing strategies and guidelines (United Nations, 1992). Some of the objectives of sustainable urban sewage systems have been proposed by Butler and Parkinson (1997) and include:

- Maintaining a public health barrier
- Preventing flooding
- Avoiding environmental pollution
- Minimising natural resource usage
- Community affordability
- Social acceptance.

One strategy to improve urban drainage sustainability is to move away from sewer networks that mix stormwater and wastewater. Normally, stormwater is not used as a resource but instead dilutes the nutrient concentration in wastewater. If stormwater were separated it could be used for watering gardens or toilet flushing, which normally uses fully treated drinking water. Negative environmental impacts can also be mitigated by using a separated sewer system as events such as CSO discharges are reduced. With very small investment, household water

consumption can be reduced by the installation of water saving appliances such as dual-flush toilets, as discussed in section 2.3.2. This will reduce water usage in households, simultaneously causing the nutrient concentration in wastewater to increase (Butler and Davies, 2004).

2.3.2- Water saving appliances.

There have been many studies aimed at assessing the effects of using water saving strategies for water conservation (Parkinson et al., 2005; Penn et al., 2014). One of the main options for water conservation is the use of water saving appliances in residential homes and other buildings. Some examples of water saving appliances include waterless washing machines, water-saving shower heads and low flush toilets. Another strategy to reduce the demand on freshwater may be the reuse of domestic greywater and rainwater (Dixon et al., 1999).

In the UK people produce 150 Litres of wastewater per day on average. Some countries produce a far lower volume of wastewater, for example, Denmark averages 80 Litres. This 150 litres/person/day is what many sewage treatment plants use in their design criteria. It is therefore important that as more houses are added to the network that water discharge per person is reduced. Waterwise, 2016 provided data on “How do we use water in the home?” which can be seen in Figure 2.3-1.

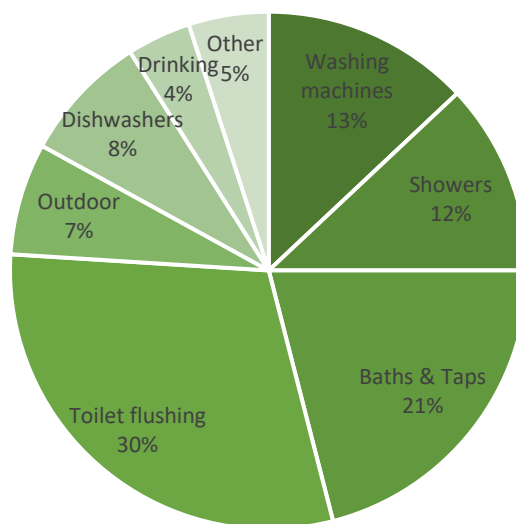


Figure 2.3-1- Water Usage in UK household's breakdown- Total usage 150 litres/person/day.

Implementing water saving appliances into current households and new build houses in the future can drastically reduce the volume of water discharged by residential homes.

As can be seen in Figure 2.3-1, Toilet flushes account for the largest proportion of wastewater production in households, with 45 litres/person/day of wastewater coming from toilet flushes. Over 7 million toilets in the UK are old, large cistern types which use between 9 and 13 litres of water per flush. Modern dual flush toilets use between 4 and 6 litres of water per flush. Dual flush toilets use two buttons to flush different amounts of water. To flush liquid waste a much lower amount of water is used, and a slightly larger quantity is used to flush solid waste. The average person flushes the toilet over 1500 times per year, so implementing these new water saving toilets would dramatically reduce the volume of wastewater produced (WTE Ltd., 2021).

Showers account for about 12 % of domestic water use. Low flow showerheads save a large volume of water compared to standard showerheads, this is because low flow heads use less than 6 litres per minute compared to the standard 9.5 litres per minute (Jorgensen et al., 2009). Aerated shower heads also reduce the flowrate of water without reducing the pressure. Pressure is maintained by mixing the water with air to produce an even spray. Aerating fixtures can also be added to other water-use appliances such as bathroom and kitchen taps and can save up to 30-50% more water. Estimates are put at 1,274 litres of water saved per month per average household using aerators (Shokory and Rabanizada, 2020).

Washing clothes accounts for about 13% of domestic water use. Steam washing machines are a more efficient option which use 40 litres of water per load compared to the 150 litres per load used by standard washing machines (Willis et al., 2006). Another type of washing machine is the Xeros waterless washing machine which uses polymer beads to give an effective wash and saves about 80 % of the water used in a standard washing machine (Burns, 2018).

2.3.3- Impact of water saving appliances on nutrient recovery.

By limiting the amount of water entering the wastewater system, dilution can be decreased, and with reduced dilution, the recovery of nutrients can become more effective. Droughts in the past have proved that a more concentrated wastewater leads to more efficient nutrient recovery. Between 1975 and 1977 there was drought across California which led to a flow reduction. The average flow reduction to wastewater treatment plants was 24% during the drought. During this period of reduced flow, BOD concentration increased by around 25 to

40% on average (DeZellar and Maier, 1980). Davis and Bursztynsky (1980) proved that with a more concentrated wastewater stream, the efficiency of treatment was improved.

According to Verstraete and Vlaeminck (2011) an average household produces a typical COD load of about 750 mg L^{-1} . In combined sewer systems, this concentration can be reduced to as much as 225 mg L^{-1} due to dilution from rainwater. For recovery using an anaerobic digester, much higher COD concentrations are required. This applies for the nutrients including nitrogen and phosphorus. There are a variety of ways to reduce the dilution in sewer networks. Firstly, separated sewer systems can increase nutrient concentration by up to 85% (Brombach et al., 2005). As discussed in section 2.3.2, using water saving appliances for 25% water conservation could increase nutrient concentration by 190% (Verstraete and Vlaeminck (2011)).

2.4- Modelling Sewer flows

Modelling has been developed to simulate drainage systems and introduce variables to observe the possible effects from real life situations, to ensure drainage systems are able to be run successfully when built.

2.4.1- Sewer modelling software- SWMM

Over the years a range of software has become available for modelling both combined and separated sewer networks, including InfoWorks and SWMM. The US Environmental Protection Agency Storm Water Management Model (SWMM) first appeared in the USA in the 1970s but has continuously been adapted and advanced to present day. These modelling programmes can model the system hydraulics and have the capability to include water quality: pollutant behaviour through the system. SWMM's core code is in the public domain and is offered with user-friendly interfaces (EPA.gov, 2021). One of the main computational blocks of SWMM is Transport which routes water flows and pollutants through a designed sewer network using the modelling basis: the kinematic wave approximation. Other computational blocks in SWMM include Runoff, Extran which uses the Saint-Venant equations and Storage/Treatment (Butler and Davies, 2004). The Saint-Venant equations are the basis of hydraulic modelling for most sewer modelling software. In terms of validity these equations are appropriate when used with the following assumptions:

- Prismatic channel;
- Velocity distribution in the channel cross-section is uniform;
- Pressure distribution is hydrostatic;
- Lateral flow is negligible.

The Saint-Venant equations can be expressed either in terms of velocity or, more commonly, in terms of flowrate. Equation 2.4-1 below shows the equation in terms of flow rate, together with the Continuity Equation 2.4-2 (Butler and Davies, 2004).

$$\frac{\partial Q}{\partial t} + \frac{\partial}{\partial x} \left(\frac{Q^2}{A} \right) + gA \frac{\partial y}{\partial x} - gA(S_0 - S_f) = 0 \quad (2.4-1)$$

$$B \frac{\partial y}{\partial t} + \frac{\partial Q}{\partial x} = 0 \quad (2.4-2)$$

Q	flow rate ($\text{m}^3 \text{s}^{-1}$)
t	time (s)
x	distance (m)
A	area of flow cross sections (m^2)
g	gravitational acceleration (m s^{-2})
y	flow depth (m)
S_0	bed slope (-)
S_f	friction slope (-)
B	water surface width (m)

To be able to model flow, the sewer system needs to be physically defined. Elements that may need to be defined in a sewer model include manholes, pipes, catchments, inflows and ancillary structures such as outfalls.

SWMM has the ability to simulate the variation in concentration of pollutants and nutrients with time through the sewer system. The flowrate and concentration vary with time in repeatable daily (diurnal) patterns. This is due to patterns in human behaviour and differences appear between weekdays and weekends. In general, the pollutants are moved through the sewer network by the liquid wastewater, and it is assumed that the pollutants move at the mean liquid velocity (Butler and Davies, 2004). The transport of pollutants with flow tends to be represented by the advection equation shown as Equation 2.4-3. Advection can be modelled as a slug of pollutant in a pipe which moves at a mean velocity without spreading out.

$$\frac{\partial c}{\partial t} + v \frac{\partial c}{\partial x} = 0 \quad (2.4-3)$$

c	concentration of pollutant (kg m^{-3})
t	time (s)
v	mean velocity of flow (m s^{-1})
x	distance (m)

In some modelling software each pipe length may be assumed to be a completely mixed ‘tank’ where all of the pollutants are fully mixed with the flow, as shown by Equation 2.4-4. This

gives estimates of concentration in each pipe as a whole. However, it does not include any distance or velocity terms meaning the progress of pollutants at mean velocity cannot be modelled using this assumption (Butler and Davies, 2004).

$$\frac{d(Sc)}{dt} = Q_1 c_1 - Q_o c_o \quad (2.4-4)$$

S	volume of liquid in pipe length (m^3)
Q_1, Q_o	flow at inlet to pipe, at outlet ($\text{m}^3 \text{ s}^{-1}$)
c, c_1, c_o	concentration in pipe length, at inlet to pipe, at outlet (kg m^{-3})

2.4.2 Deterministic and Stochastic modelling

Deterministic modelling techniques have mainly been used so far to show gross solids movement in sewers. Penn et al. (2014) modelled gross solid movement with different levels of grey water recycling uptake. The problem with using deterministic modelling for domestic wastewater arises due to the fact that the wastewater is assumed as a continuous discharge based on averaged data which basically assumes all people have the same water use pattern. However, household discharge profiles are a non-continuous series of discrete points which can be better modelled using a stochastic model. A stochastic model assumes humans are predictable and there is a probabilistic element to household water usage. Blokker et al. (2010) produced a stochastic model for drinking water (SIMDEUM) based on statistical data rather than flow measurements. SIMDEUM was developed further by Pieterse-Quirijns et al. (2012) to include appliance specific discharge qualities, called SIMDEUM WW.

By combining SIMDEUM and SIMDEUM WW it is possible to relate the appliance specific pollutant qualities with discharge pulses, determined from diurnal patterns. Bailey et al. (2019) developed a graph to show the difference between a deterministic model and stochastic model for household discharge patterns, as shown in Figure 2.4-1.

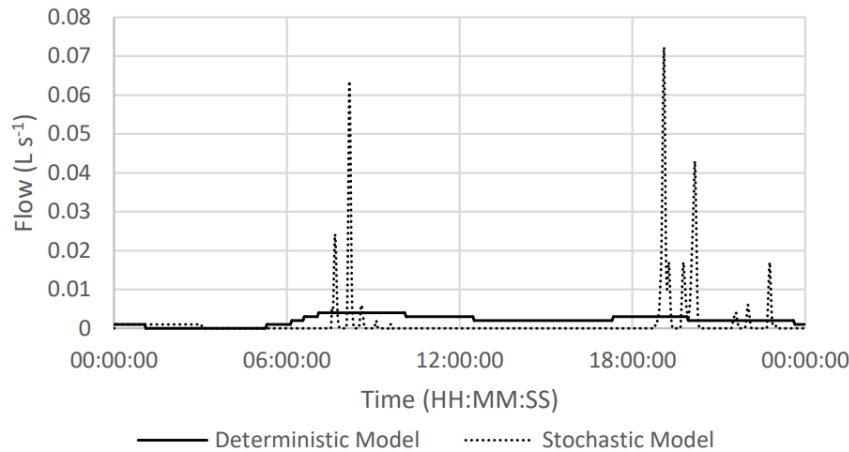


Figure 2.4-1- Deterministic model compared to Stochastic model for household discharge.

Bailey et al. (2019) developed a hydraulic sewer model to incorporate stochastic discharge patterns. In that research the patterns were linked with the InfoWorks ICM software to produce outputs and was also validated using data from real catchments. The work deemed the stochastic model to be more representative of a real system than a deterministic model. The research also tested five future scenarios. This testing showed that a 15-60% reduction in domestic water use led to concentration increases of COD, TKN and TPH by 55-180%, 19-166% and 30-206% respectively.

2.5- The future of water use

In the UK, domestic water demand has been increasing since the 1950s due to a rapidly increasing population. As population continues to rise, urban areas will need to be expanded, and therefore so will the sewer networks. With more households connected to the sewer networks, the flow of water entering the sewer systems will increase, dilution will increase and nutrient concentrations will decrease, meaning nutrient recovery and water treatment will become more inefficient.

Sewer systems tend to be built to last for many decades and as technology advances these systems may not be suitable anymore, for example, pipes may be extremely oversized if water saving appliances are installed into homes. Sewer systems need to be tested and modelled with

a variety of future water use scenarios whether it be new regulations or changes in domestic appliances, and then built to be long lasting systems with the capability of transporting sewage away from urban areas.

2.6- Concluding Remarks

The world's population is continuously growing, and water is becoming a more and more valuable and scarce resource. Urban sewage systems are heading away from being combined networks and towards separated systems to aid in effective water treatment. To be able to help conserve water and improve water treatment efficiency, one strategy that could be implemented is to use water saving appliances in domestic dwellings. This will reduce the flow of water into the sewage systems and increase the nutrient concentrations, aiding in nutrient recovery processes. A variety of modelling tools, such as SWMM, are available to hydraulically simulate sewer networks under a range of different conditions. Using these simulations, results can be produced of flowrates and nutrient concentrations in wastewater. Many simulations can be run under different conditions to determine the effects of a changing future.

2.7- Aims and objectives

The overall aim of this research is to develop a stochastic sewer model that can deal with changes in future water use, such as water saving appliances, and allows wastewater flow and quality to be observed and simulated. This is necessary as the urban water cycle heads to a more sustainable future. The objectives of this project to achieve this aim are as follows:

1. Produce stochastic water discharge patterns using SIMDEUM calibrated to the UK population based on data found through research.
2. Define wastewater quality profiles for typical household water use appliances and use SIMDEUM WW to create wastewater discharge profiles for different house types.
3. Input the nutrient discharge profiles into the modelling programme SWMM for the sewer network of a case studied residential catchment area.
4. Explore and test future water saving household appliances, including a water saving toilet, shower head and a waterless washing machine, to observe the effect of flow into the sewer network and the concentration in the wastewater to see potential effects on water treatment processes.

3. Case Study

3.1- Site Description

The site selected for this research project is a future development, The Hangar District in Brabazon, Filton near Bristol in the south-west of the UK. Brabazon is designed to be a thriving new neighbourhood for Bristol and will be the first major UK mixed-use scheme by YTL Developments. YTL Developments is an innovative company aiming to create sustainable communities that meet the needs of people now and in the future, whilst promoting happiness, wellbeing, and creativity of people in the community. Overall Brabazon will be a 354-acre plot with over 2600 new homes, offices in an Enterprise District, schools, a train station, parks, and stores.

This project will focus only on the sewage network of residential houses from the first stages of building of The Hangar District, consisting of 80 houses and an apartment block, namely the Navigator Building. These 80 houses can be broken down more specifically into 8 two-bed houses, 60 three-bed houses and 12 four-bed houses, and the apartment block is a mix of one and two bed apartments with a total of 33 apartments. The first development stages that this research project will produce a sewage model for can be seen highlighted in the orange box of Figure 3.1-1.

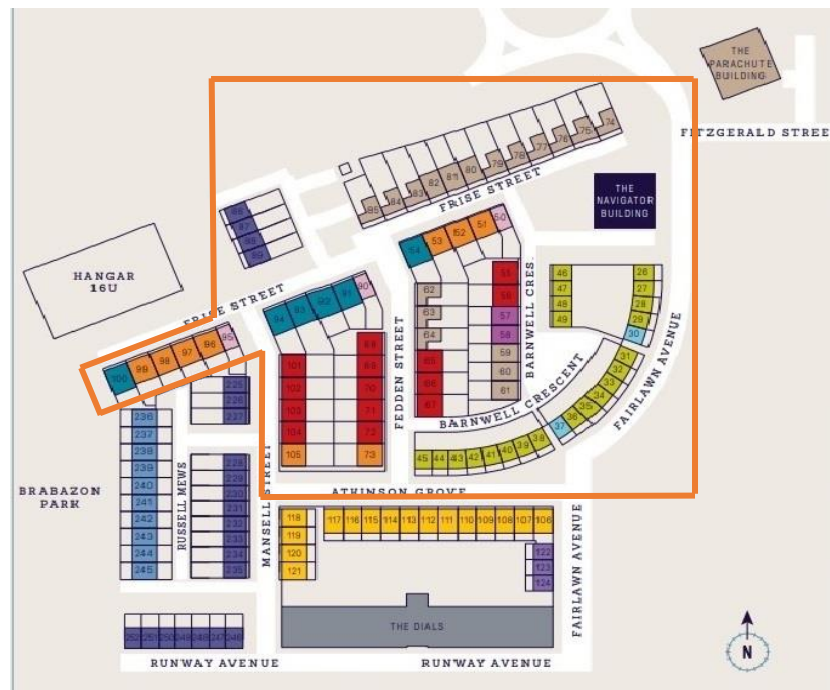


Figure 3.1-1- Plan of The Hangar District residential areas.

Using information provided in a brochure produced for the Hangar District (The Hangar District, 2021), the different houses shown in Figure 3.1-1 could be classified into sizes by bedroom number and their floorplans allowed for an assessment of the sources of wastewater into the sewage network, as can be seen summarised in Table 3.1-1.

Table 3.1-1- Breakdown of house types of The Hangar District (The Hangar District, 2021).

Colour on Figure 3.1	House Type	Plot numbers	Number of Bedrooms	Number of Ensuities
	The Sycamore	57, 58	2	0
	The Boxkite	50, 90, 95	2	0
	The Badminton	55, 56, 65-72, 101-104	3	1
	The Prier	51-53, 73, 96-99, 105	3	1
	The Seely	26-29, 31-36, 38-49	3	1
	The Pullman	54, 91-94, 100	4	2
	The Brandon	86-89	4	2
	The Scout	30, 37	4	1
	Affordable 2-bed	59-61	2	0
	Affordable 3-bed	74-85, 62-64	3	0

Every house type was found to have one main bathroom, which contained an over-bath shower, a WC and a basin, as well as a separate WC. The wastewater from the kitchen of every house type came from a combination of the kitchen tap, dishwasher and a washing machine. The ensuities of each house type that had one were assumed to contain both a WC and a shower. All house types were also found to have an outdoor tap. The one and two-bed apartments did not have outdoor taps and only the two-bed apartments had ensuite bathrooms, with both having the same standard bathrooms as the house types. Both apartment types also contained the same kitchen appliances as the houses. An example of the floorplan where this information was found can be seen in Figure 3.1-2 which represents a one-bed apartment of the Navigator Building.

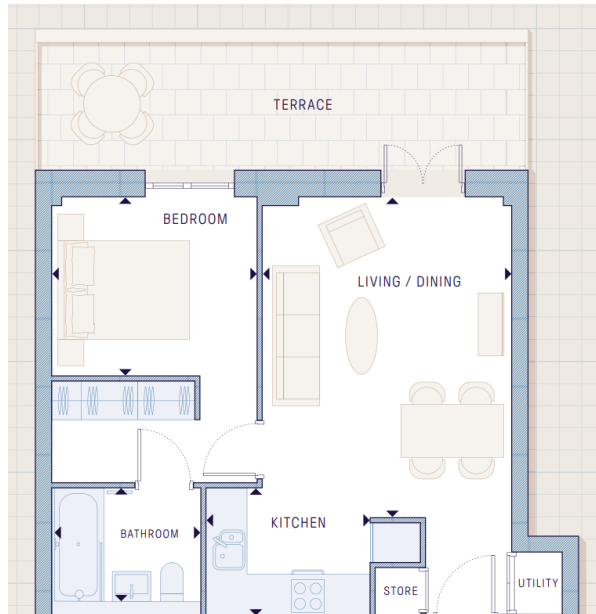


Figure 3.1-2- Floorplan showing rooms and appliances of a one-bed apartment.

The relevant information that was used to determine the bedroom numbers and number of ensuites per house type for the first stages of building was found in *Appendix 7: Resi Phase 1 Full Development Metrics*. An extract of that excel file can be seen in Figure 3.1-3. Using a COUNTIF function in excel it was quick and easy to find the bathroom and ensuite numbers for each house type.

1
2
3
4
5
6
7
8

A

B

C

D

E

F

G

H

I

J

K

L

M

N

O

BRABAZON

APPENDIX 7: Resi Phase 1 Full Development Metrics

Phases 1A to 1D

Note: Block A&B Updated RIBA Stage 4 Areas

Note: Sales & Construction Information to be Confirmed

Block B

Block A

Block J

Previous Plot	Updated Plot	HOUSE TYPE	LOCATION	TENURE	BALCONY / ROOF TERRACE		STOREY	UNIT NOS.	APARTMENTS	FLOOR LEVEL	CAR/P BAYS	BED/RM	BATH	EN-SUITE
					M²	FT²								
		SUB-TOTAL			92	995		33			33	54	33	21
		LANDED HOUSING												
50	26	26	TYPE E2	END UNIT	OPEN MARKET	40	425	3	1		2	3	1	1
51	27	27	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
52	28	28	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
53	29	29	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
54	30	30	TYPE E3	END UNIT	OPEN MARKET	37	397	3	1		2	4	1	1
55	31	31	TYPE E1	END UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
56	32	32	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
57	33	33	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
58	34	34	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
59	35	35	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
60	36	36	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
61	30	30	TYPE E3	END UNIT	OPEN MARKET	37	397	3	1		2	4	1	1
62	38	38	TYPE E1	END UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
63	39	39	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
64	40	40	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
65	41	41	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
66	42	42	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
67	43	43	TYPE E1	INTERMEDIATE UNIT	OPEN MARKET	36	385	3	1		2	3	1	1
68	44	44	TYPE E2	INTERMEDIATE UNIT	OPEN MARKET	40	425	3	1		2	3	1	1
69	45	45	TYPE E2	END UNIT	OPEN MARKET	40	425	3	1		2	3	1	1

Metrics 200217

<

Figure 3.1-3- Extract from Excel file for housing metrics of Brabazon Development.

3.2- Sewer Network Description

The sewer network for the housing residential area shown in Figure 3.1-1 was developed in SWMM. For this residential development, a separated sewer network was developed, meaning it excludes storm water. The sewer network is a gravity driven system with the outfall being the lowest point of the network and the furthest house from the outfall being the highest point, i.e., plot 74. There are inflow junctions from each house or apartment block and all nodes are connected by conduits. From the outfall the wastewater may be taken to a water treatment plant, where nutrients in the wastewater can be extracted. The pipe network containing all junctions, nodes, conduits, and outfall can be seen in Figure 3.2-1.

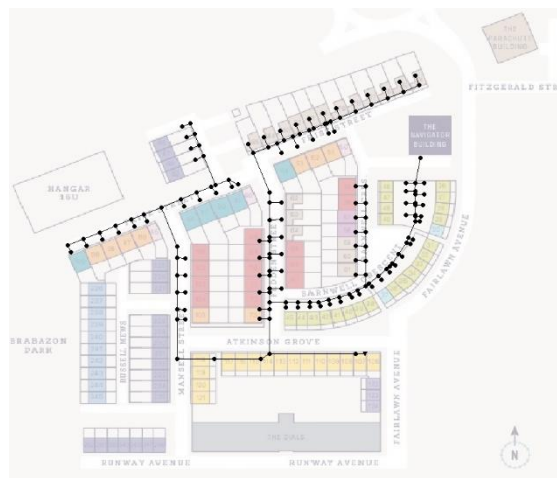


Figure 3.2-1- Sewer network overlaid onto housing map.

Using the SWMM software it is possible to produce a cross-sectional view of the separated sewer network, from plot 74 to the outfall. This cross section can clearly demonstrate the gravity driven nature of this network, as can be seen in Figure 3.2-2.

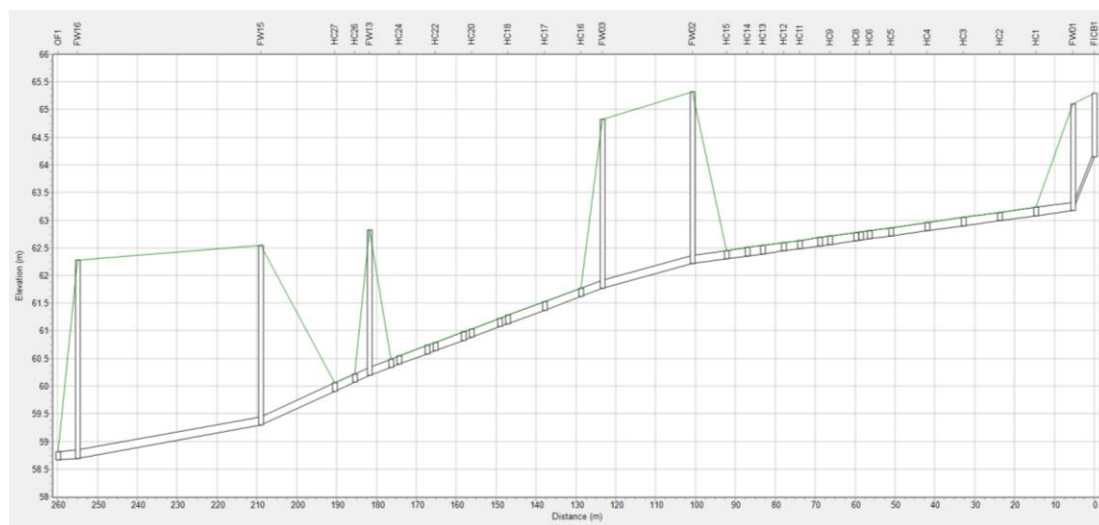


Figure 3.2-2- Cross sectional view of the sewer network from highest to lowest point.

The vertical pipes shown in Figure 3.2-2 demonstrate manhole locations from street level to the sewer pipes along the network. Each conduit was assigned a roughness factor of 0.01 and the conduits were all circular closed. FICB1 is the highest point of the network at 64.15 m and is the inflow from the house at plot 74, whilst the outfall is the lowest point at 58.665 m giving an overall elevation change of -5.485 m. Each node shown in Figure 3.2-2 could contain inflow from one or more houses in the network. For example, node HC1 contains inflow from FICB2 which is plot 75 of the housing network.

4. Methodology

4.1- Modelling approach

The approach taken to model the sewer system for The Hangar District was to combine two existing modelling tools: SIMDEUM and Storm Water Management Model (SWMM). SIMDEUM is a pattern generating tool offered by Watershare and is used to firstly create a stochastic model for an estimation of water discharge and temperature discharge patterns from households. SIMDEUM WW was then used to create a stochastic wastewater discharge element based on appliance-specific discharge parameters such as nutrient loads in the wastewater. These patterns were then incorporated into the SWMM software by editing MATLAB codes behind SIMDEUM which produced file types that could be inputted into the SWMM programme. Future water saving technologies were then simulated in the model and the effects of the flow and nutrient concentration in the wastewater were observed.

SIMDEUM was originally developed as a software tool in the Netherlands to model water demand patterns, using a combination of statistical and probabilistic information about inhabitants and appliance usage (Blokker et al., 2010). SIMDEUM was used in this research as it is able to produce discontinuous, random flow patterns distinctive of wastewater sewer systems. The SIMDEUM pattern generator (SPG) tool was supplied by Watershare and the calibration for this pattern generator is described in Section 5. The SPG tool is coded in MATLAB to provide a user-friendly interface without editing information within the code script of the programme, which can be seen in Figure 4.1-1.

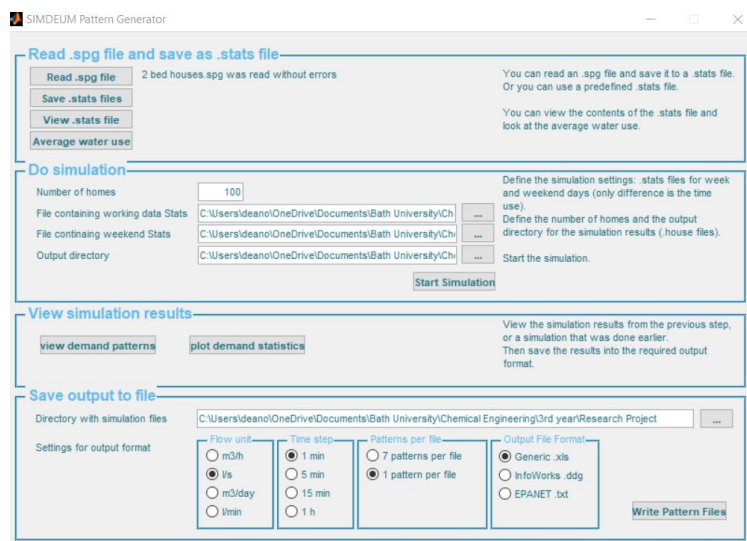


Figure 4.1-1- SIMDEUM Pattern Generator User-Friendly Interface

The SPG works firstly by reading an .spg file which is user-produced in the Watershare tool and then saving the information in the .spg file as a week.stats file and a weekend.stats file, as can be seen under the “Read .spg file and save as .stats file” header of Figure 4.1-1. These .stats files can then be used to run a simulation of the water demand patterns which can then be plotted as time series graphs. More information on the creation of the .spg files can be found in Section 5.

SIMDEUM WW is an extension of SIMDEUM and was used to assign appliance-specific **wastewater quality profiles** to each wastewater discharge. Certain appliances have similar demand and discharge patterns, for example, the shower running to the drain, however, other appliances such as a toilet or washing machine may discharge much faster than they are filled. By using SIMDEUM and SIMDEUM WW together it is possible to produce probabilistic **discharge pulse flows into the sewer network**. Unlike for the SPG, however, there has been no user-friendly interface built for the SIMDEUM WW programme, meaning these wastewater

quality profiles were developed within the MATLAB code of SIMDEUM WW to produce time series .dat files to be integrated into SWMM. A separate time series file was required for each parameter, i.e. time series files for each house type and each nutrient, Nitrates (N), Phosphates (P), Chemical Oxygen Demand (COD) and suspended solids (SS). Separate time series files were also needed for the water-saving appliances situations. The water saving appliances investigated in this project were a water-saving shower head, a waterless washing machine and water saving toilets.

SWMM was used to simulate the residential case study as a separated sewer network and produce a stochastic sewer model based on the output .dat files from SIMDEUM WW. Time steps of 1 minute were used and the simulations were conducted over a 5-day period, the weekdays. The SWMM software could then produce a time series at the outfall of the network showing the cumulative flow and concentrations collected from the network over the simulated period.

5. Data and model calibration

SIMDEUM was originally calibrated for the Dutch trends of water use and applications and therefore SIMDEUM required different input parameters which would better describe the UK in terms of information about household sizes, diurnal patterns, and appliance usage. By gathering data based on the UK population it was possible to input parameters which described UK habits more accurately than the average Dutch households' habits. This could then be used to calibrate a stochastic model and produce patterns that are more suited to the case study area of Brabazon in the UK.

5.1- Data Collection

The first stage of calibrating SIMDEUM to the UK population was to gather data that could be inputted into the Watershare tool to create .spg files. Watershare required 3 sections of information: Regional Household Statistics, Time Budget Data and Installation & Consumption, as can be seen in Figure 5.1-1.

Water-use Info 1.0.14 watershare®

1 Regional Household Statistics → 2 Time Budget Data → 3 Installation & Consumption

Download SPG

Import data

Area: UK

Regional Household Statistics

Household division ?

All form fields are required.

Percentage one person household: 30.0

Percentage two person household: 37.0

Percentage more person household: 33.0

OK Cancel

One person household - age division ?

Two person household - age division ?

Family - age division ?

One person household - gender division ?

Two person household - gender division ?

Family - gender division ?

One person household - labour division ? 67,552.4

Two person household - labour division ? 49,426,063,183

Family - labour division ? 38,633,313

Figure 5.1-1- Watershare tool used to create .spg files.

The Regional Household Statistics section required information describing the household occupancy and as can be seen in Figure 5.1-1 households are characterised into 3 types: one

person, two person and more than two person households, i.e. a family. These household sizes were then also divided based on gender, age and labour. This household statistics data was found through ONS, 2011.

The next section, Time Budget Data, required information on households' diurnal patterns for each age group, and divided into weekdays and weekend days. A United Kingdom Time Use Survey had been conducted in 2014-2015 by Sullivan, O., University of Oxford. This large-scale household survey provided data on how people in the UK use their time. Effectively, the survey provided a time diary instrument where participants would record their daily activities. This survey provided the necessary information on when people were waking up, leaving their house, returning home, and going to sleep, as can be seen in Figure 5.1-2.

Child - diurnal pattern weekend	
Average time of getting up (HH:MM)	7:57
Standard deviation around time of getting up (HH:MM)	1:00
Average time of leaving the house (HH:MM)	9:35
Standard deviation around time of leaving the house (HH:MM)	1:00
Average duration of being away from home (HH:MM)	8:50
Standard deviation around duration of being away from home (HH:MM)	1:30
Average duration of sleeping (HH:MM)	10:24
<input type="button" value="OK"/> <input type="button" value="Cancel"/>	

Figure 5.1-2- Extract of required data in Watershare for Time Budget Data.

The survey data was provided in a large Excel sheet which had to be sorted through to find the necessary information. An extract from the survey data can be seen in the Appendix, Figure A-1, of this report. The data was in a key format, where each number in the survey summary corresponded to a specific activity. An example section of this key can also be seen in the Appendix, Figure A-2. The survey was conducted for corresponding age groups to what was required in Watershare. For example, the survey was conducted on the age groups 8-12, 13-18, 19-64 and 64+ year olds which corresponds to the titles on Watershare of child, teen, adult and senior respectively. The adult age group was also further divided into working adults and non-working adults. Using COUNTIF functions in excel, the survey information could be refined

into the necessary data required for the Watershare tool. As an example, Table 5.1-1 shows necessary information for 8-12 year olds on a weekend day for the hours of 04:00 to 05:00.

Table 5.1-1- Information on when 8-12 year olds sleep and when they are not at home.

Time	Total	Sleeping	Fraction sleeping	Not at home	Fraction not at home
04:00:00	564	561	0.994681	80	0.141844
04:10:00	564	558	0.989362	83	0.147163
04:20:00	564	560	0.992908	81	0.143617
04:30:00	564	558	0.989362	82	0.14539
04:40:00	564	559	0.991135	81	0.143617
04:50:00	564	558	0.989362	82	0.14539
05:00:00	564	556	0.985816	81	0.143617

This information on when people are sleeping and when they are away from home can be plotted to represent the general pattern. As can be seen in Figure 5.1-3 there is a clear trend of people being awake during the day between approximately 7:00 AM and 8:00 PM and if people are not at home, this tends to also be during the day, when people are awake and leaving the house for other activities.

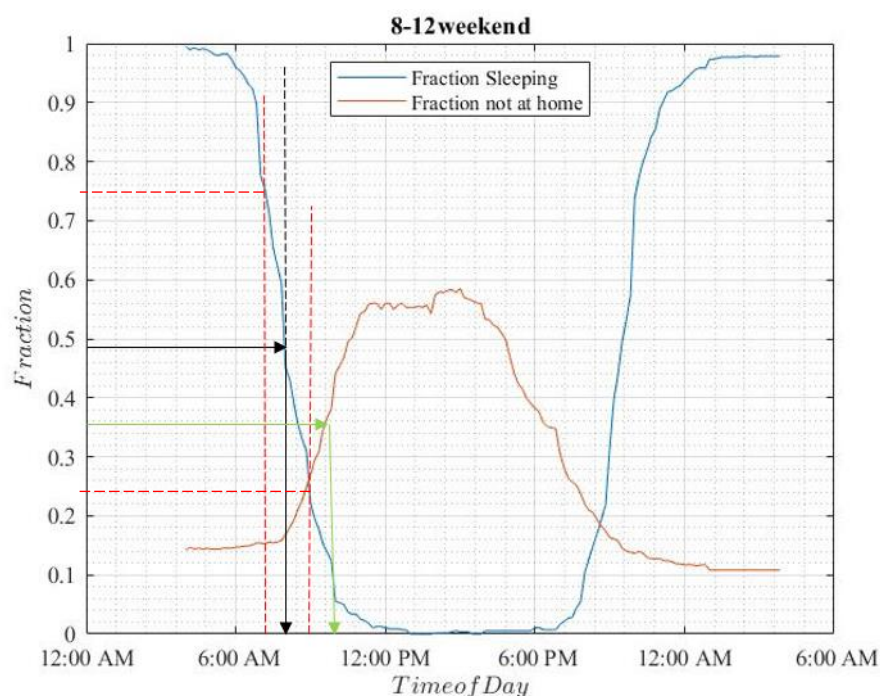


Figure 5.1-3- Daily trend of when 8-12 year olds are sleeping and at home

To find the average time people wake up, the midpoint fraction of the highest and lowest point of people sleeping was found as 0.481 as shown by the black arrow on Figure 5.1-3. This corresponded to a wake-up time of 7:57 AM. To find the average time of leaving the house, a

similar procedure was followed as shown by the green arrows. The midpoint fraction of the peak of people being away from home and the low point of people being at home was found as 0.355 which corresponded to an average leave time of 9:35 AM. Similar procedures were followed to find the average times of people returning home and going to sleep. Using these times, it was possible to work out the average duration of people being away from home as well as the average duration of people sleeping, required for the Watershare Tool.

Other necessary data that had to be inputted into the Watershare Tool was the standard deviations around the times and durations calculated. Under standard deviation rules, 68% of the data lies within one standard deviation from the mean. The red dashed lines on Figure 5.1-3 therefore show the method for calculating the standard deviation around the time of getting up. 68% was calculated of the number of people awake at the average wake up time and then subtracted and added to the mean. These fractions were then read across to find the time standard deviation and an approximate standard deviation of 1:00 was found for the time of waking up, as shown by the red dashed lines. A similar procedure was then followed to find the standard deviations around the time of leaving the house, duration spent away from home, and duration sleeping, as can be seen necessary in Figure 5.1-2.

This same procedure was followed for each age group and for each day type (weekday and weekend) and the results shown in Table 6.1 were inputted into the Watershare Tool under the Time Budget section.

The final section for the Watershare Tool was the Installation and Consumption section. Water demand in households depends on the number of water-using appliances in the house, for example a shower, a bath, two toilets, etc. as well as the characteristics of the appliances, such as frequency of use, flow rate, duration of use and desired temperature. Depending on the user of the appliance, the duration and frequency can vary, for example a senior may flush the toilet more often than a teen whilst a teen may take longer and more frequent showers than a senior. Further to this, the duration, frequency, and desired temperature of the appliance can vary from appliance to appliance as well as the application of the appliance. These different applications can be added as subtypes of the appliance in the Watershare Tool, for example a bathroom tap may run hot water for shaving, but cold water for teeth brushing. Due to time constraints and the current unavailability of data in the UK situation, the installation and consumption input

sections were taken from demo files provided by the SPG programme. It was therefore assumed that while there may be differences in the household statistics and the time budget data between the Dutch and UK situations, the use of appliances between the two situations is the same. Figure 5.1-4 shows some of the inputted data into the Watershare Tool for the Installation and Consumption section, taken from the demo_2014 file provided by the SPG.

The screenshot displays the Watershare Tool interface. At the top, there are tabs for different appliance categories: Bath-bath, Bathroom tap-bathroom_tap, Dishwasher-dw, Kitchen tap-kitchen_tap, Outside tap-outside_tap, Shower-shower, Washingmachine-wm, Toilet-wc1, and Toilet-wc2. Below these tabs, there are input fields for various parameters:

- Penetration ? : 100.0
- Child - frequency ? : 3.800,5.400,4.600
- Teen - frequency ? : 4.100,5.100,4.700
- Working adult - frequency ? : 5.300,6.800,6.000
- Home adult - frequency ? : 7.000,7.000,7.000
- Senior - frequency ? : 7.400,6.800,7.200
- Total - frequency ? : 5.300,6.400,5.900
- Daily pattern ? : NONE
- Offset ? : 0.0
- Name ? : (empty field)

A red box highlights a window titled 'wcSavePlus' which contains the following input fields:

- Penetration ? : average
- Duration ? : 2.4
- Flow ? : 0.042
- Temperature ? : 10.0

Figure 5.1-4- Installation and Consumption of Watershare Tool

For the normal household appliance situation there was no subtype for the shower, toilet or washing machine. However, for the water saving appliances situation subtypes were added to each of these appliances. For the toilets, a wcSavePlus subtype was added to each, for the washing machine, a waterless subtype was added and for the shower, a water saving shower head subtype was added. The water saving shower head reduces the flowrate of water, the waterless washing machine fills with less water and the SavePlus toilet fills its reservoir for less time at the same flowrate, meaning a decreased reservoir volume and therefore less water into the sewer network per flush.

5.2- SIMDEUM

Once all 3 sections of the Watershare Tool had been completed, the data could be saved and exported into an .spg file type. If necessary, these .spg files could be opened in a notepad app as .txt files and be easily manipulated.

Using the downloadable SPG from the Watershare Tool, the .spg files could be read and saved as .stats files as shown in Figure 4.1-1. Using the SPG interface it was possible to view the household statistics information of the .stats files. **This information on household statistics is summarised in Figure 5.2-1 for 2-bedroom house types.** The distribution of single, two person and family households is defined in the middle of Figure 5.2-1 and the other parameters including age, gender and labour division are shown around the edge.

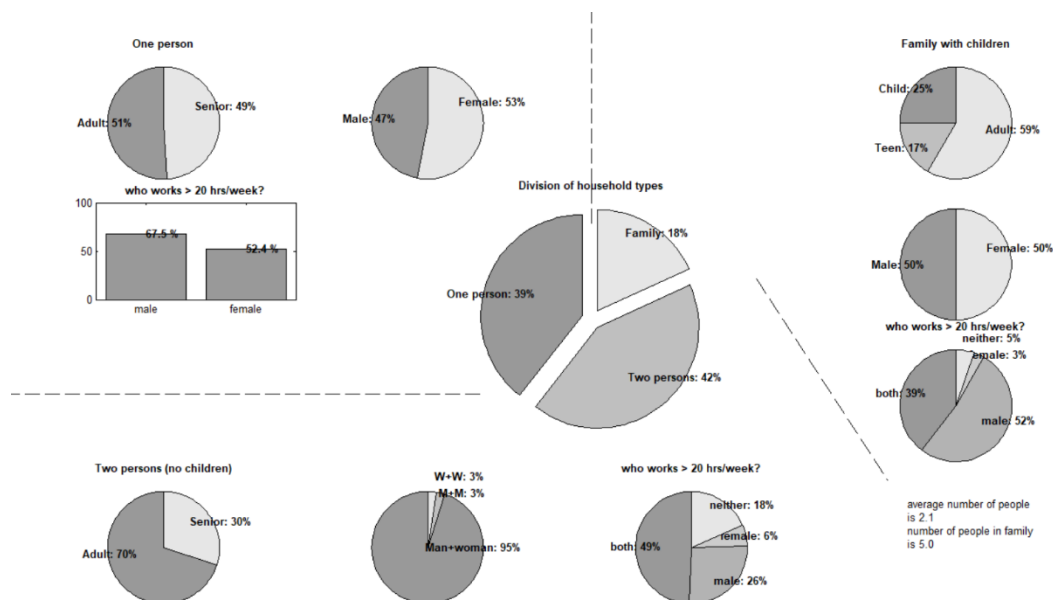


Figure 5.2-1- Household statistics data for the UK situation- 2 bedroom houses

Using this household occupancy information as well as the time use data summarised in Table 6.1, together with the water consumption information for each appliance, SPG was able to run a simulation and produce discharge profiles for each house type, as shown for example by Figure 5.2-2.

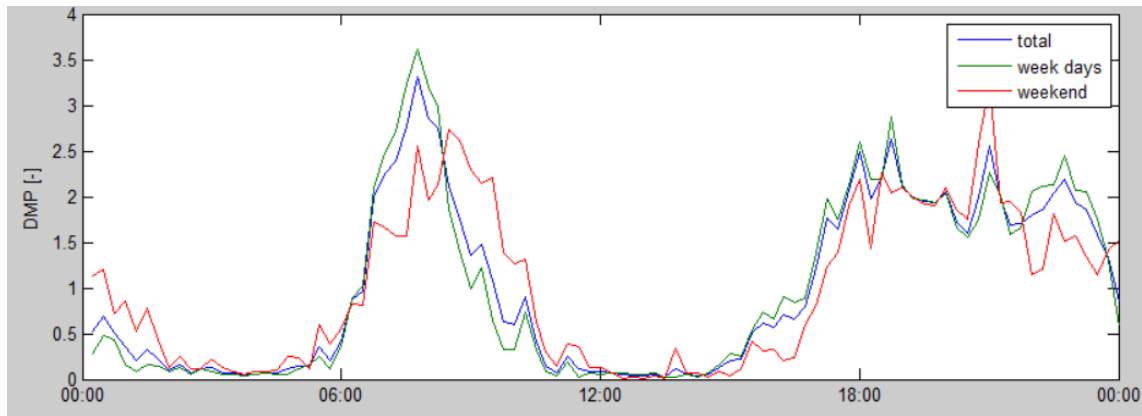


Figure 5.2-2 - Total flow discharge profile for 2 bed house type.

5.3- SIMDEUM WW

The next stage was to input these discharge profiles for each house type into the SIMDEUM WW code to produce appliance-specific wastewater quality profiles. Appropriate input values for the pollutant discharges were found and are summarised in Table 5.3-1 (Bailey et al., 2020). Discharge qualities may come from a variety of sources, for example, detergents, food scraps, human waste etc. These discharge qualities were added to MATLAB code as fixed input values. As the discharge qualities shown in Table 5.3-1 are in g use^{-1} the code was altered to convert the concentrations into g L^{-1} . This was done by taking the discharge profile and dividing it by the flowrate, measured in L s^{-1} . The code in MATLAB was then run to produce .dat files of the water discharge quality patterns for each nutrient type and then each house type with either normal appliances or water saving appliances.

Table 5.3-1 - Appliance specific pollutant concentrations

Household appliance	Discharge Temperature (°C)	Discharge sewage quality (g use ⁻¹)			
		N	P	COD	SS
Shower	35	0.49	0.00	12.60	4.32
Toilet	23	0.22	0.90	11.22	3.04
Kitchen Tap	40	0.35	0.03	7.48	4.68
Bath	36	0.85	0.00	25.90	8.88
Bathroom Tap	40	0.04	0.00	1.48	0.56
Washing machine	(35, 35, 35, 40)	0.64	0.00	65.25	17.10
Dish washer	35	1.35	0.00	30.00	13.20

5.4- SWMM

Using the files produced from SIMDEUM WW these stochastic household discharge profiles were integrated into the sewer network developed within SWMM, shown in Figure 3.2-1. Each house has a node which can be matched to a specific time series, e.g. a time series of flow rates or a time series of nitrogen concentration. SWMM runs the wastewater quality model alongside the hydraulic model to produce realistic patterns. The concentration at every node is calculated for every time step, following the conservation of mass. It is assumed that the nodes are well mixed and there is no deposition or accumulation along the system. Dispersion along the conduits is also assumed to be negligible in SWMM and pollutants move through the conduits at a constant velocity. The SWMM simulation can then be run and the time series that results at the outfall for the 5-day period can be exported to Excel.

The procedure followed in this research project can be seen summarised in Figure 5.4-1.

**Figure 5.4-1 - Outline of procedure followed.**

6. Results and discussion

6.1- Calibration Results

Using data found through ONS, as described in Section 5.1, the occupancy of each household type could be found, as shown in Figure 6.1-1. In the Navigator building there are 12 one-bedroom apartments and 21 two-bedroom apartments, so the average apartment occupancy was found as a weighted average of the one and two bedroom house types for the specific case study of the Navigator Building. An expected trend can be seen in Figure 6.1-1, as the house type gets larger the number of occupants increase, as can be seen by the fact that the percentage of 1-bedroom houses with 2+ persons is 3% whereas for 4-bedroom houses it is 51%. These occupancy values were used in the ‘Household Statistics’ section of the Watershare tool in the creation of the .spg files for each house type.

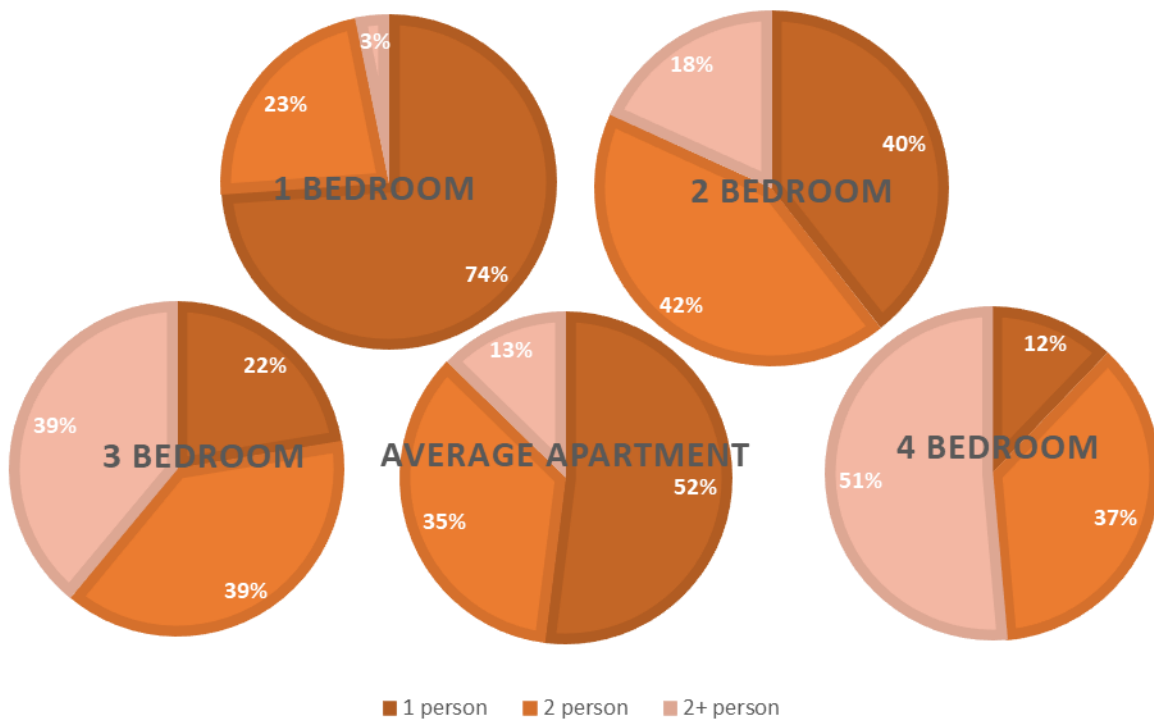


Figure 6.1-1-Occupancy for each house type.

Using the Oxford data as described in Section 5.1 the diurnal behaviour of each age group could be found for each day type, weekday, or weekend. The diurnal pattern for 8-12 year olds on the weekend can be seen in Figure 5.1-3 previously. The diurnal patterns for each other age group follows a similar trend and the average diurnal pattern for all age groups can be seen in Figure 6.1-2 for weekdays and Figure 6.1-3 for weekend days.

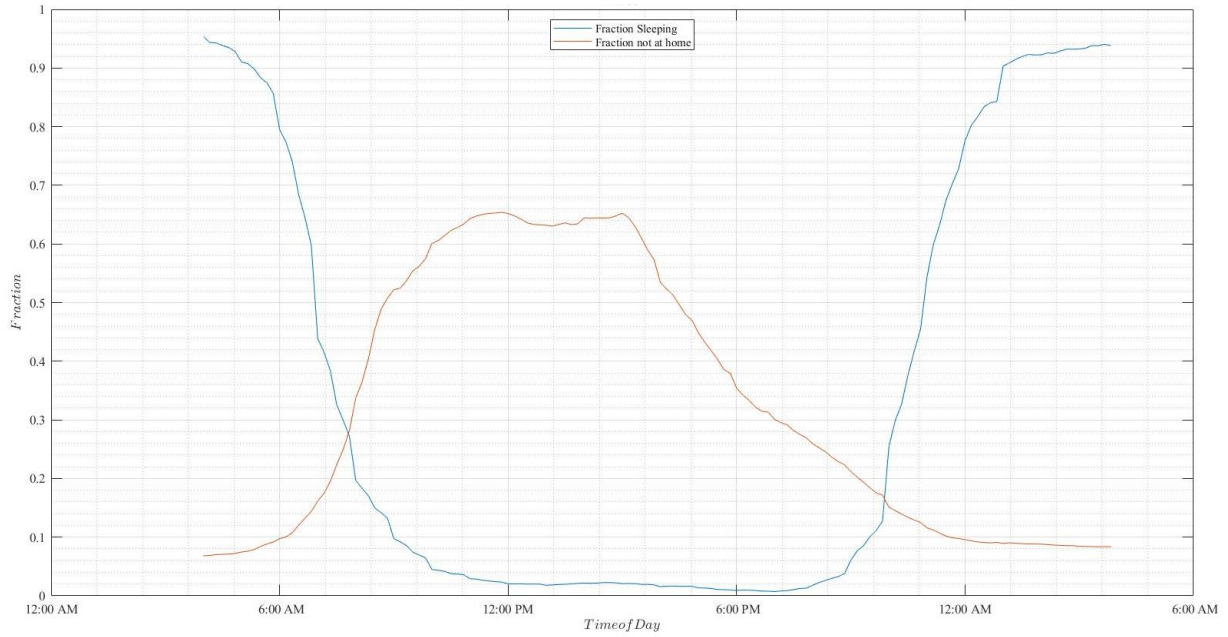


Figure 6.1-2- Average weekday diurnal pattern.

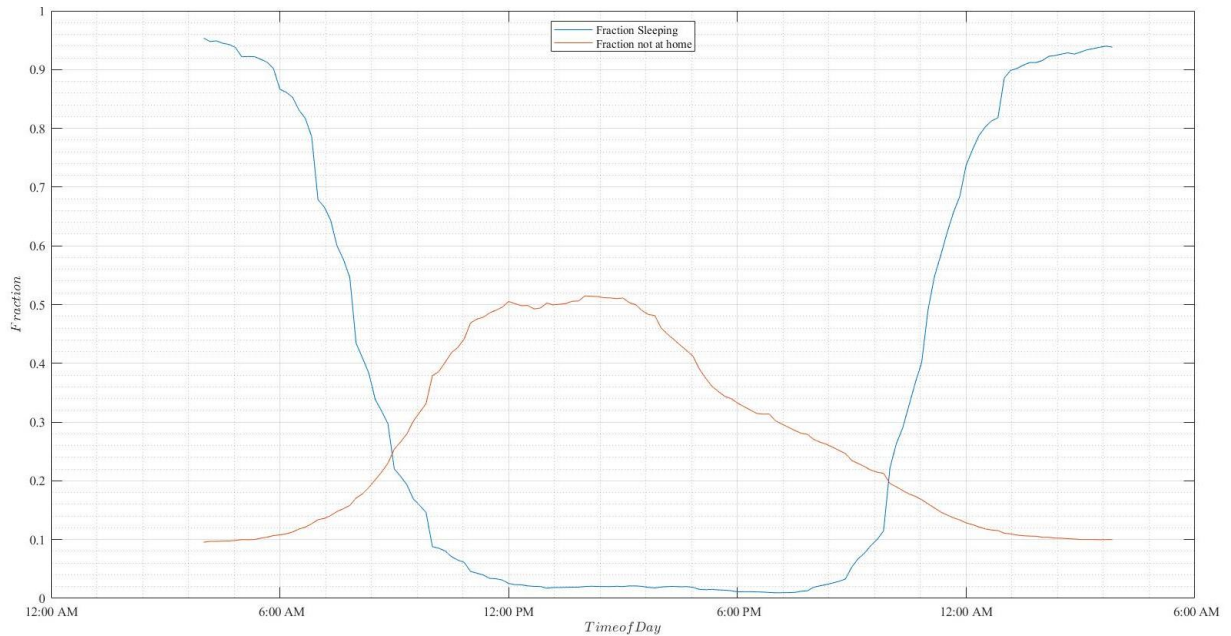


Figure 6.1-3- Average weekend diurnal pattern.

As can be seen in Figures 6.1-2 and 6.1-3 people tend to be awake during daytime hours and if people are away from home it tends to also be during the day. The fraction of people away from home at 12:00 PM is about 15% lower during the weekends, which fits the trend of people leaving home for work during the week. Using these graphs for each age group the average wake up times, average time of leaving the house, duration of being away from home, duration of sleeping and their standard deviations could all be calculated as described in Section 5.1 and

these results are summarised in Table 6.1-1, where μ shows the average, σ shows standard deviation, week stands for weekday and Wend stands for a weekend day.

Table 6.1-1- Summarised Time Budget Data for the UK situation.

		Time Waking Up		Time Leaving House		Duration Away		Duration Sleeping	
		μ	σ	μ	σ	μ	σ	μ	σ
Child	Week	07:11	0:30	08:20	0:40	8:00	1:00	9:56	0:30
	Wend	07:57	1:00	09:35	1:00	8:50	1:30	10:24	1:30
Teen	Week	07:17	0:50	08:02	0:45	8:38	1:30	8:46	0:50
	Wend	09:10	0:50	10:35	0:45	9:17	2:30	10:12	1:00
Working Adult	Week	06:31	0:30	07:44	0:30	9:32	1:15	7:34	0:30
	Wend	06:58	1:15	08:01	1:00	10:54	2:00	7:50	1:00
Home Adult	Week	07:22	0:30	08:45	1:30	9:46	1:30	8:20	0:50
	Wend	07:59	0:50	09:52	1:30	8:48	2:00	8:51	1:00
Senior	Week	07:15	0:45	09:17	1:00	7:32	1:30	8:15	1:00
	Wend	07:35	1:10	09:35	1:00	7:48	2:30	8:32	1:20
Total	Week	06:59	1:00	08:09	0:50	9:48	1:10	8:07	0:50
	Wend	07:55	1:30	09:31	1:30	9:29	2:00	8:57	1:30

The data shown in Table 6.1-1 was inputted into the **Watershare Tool** under the 'Time Budget' section for the creation of the .spg file types necessary for SIMDEUM.

6.2- Simulation Results- Flow Rate

Once SIMDEUM and SIMDEUM WW had been run using the calibrated model, the output files could be run in SWMM to produce time series data for the wastewater flowrate and the nutrient concentrations at the outfall. The simulation was run for a 5-day period for both the situations of using normal household appliances and water saving household appliances. Figure 6.2-1 shows the wastewater flow rate ($L s^{-1}$) for both household appliance scenarios where NA is normal appliances and WSA is the water saving appliances.

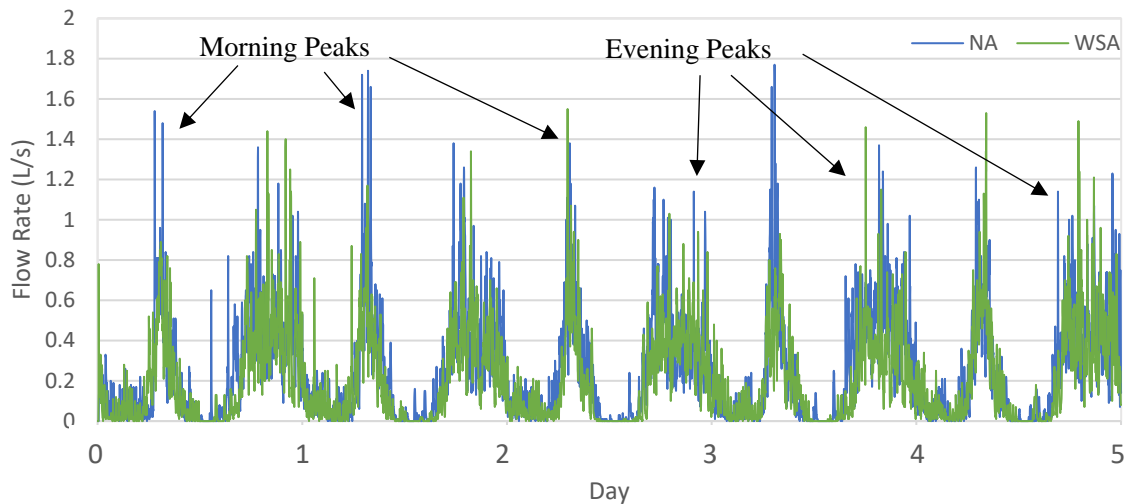


Figure 6.2-1- Wastewater flowrate at network outfall for a 5-day period.

A clear diurnal pattern can be seen in Figure 6.2-1 with both morning peaks and evening peaks. The morning peaks are sharper while the evening peaks are more spread out. This is because people all tend to start work and school at the same time in the UK, around 9:00 AM meaning people tend to shower etc. around the same time before work or school. In the evenings people finish work or school over a larger range of times so the spread of when people are using the water consuming appliances is larger. People also tend to be awake and at home for more hours after work than they are before work, meaning they may use the toilet or taps more times, which explains the wider spreader in the evening peaks.

In order to compare the effects of using water saving appliances compared to normal appliances, a period of 1 day was chosen to clearly demonstrate the difference, as can be seen in Figure 6.2-2, with day 1.

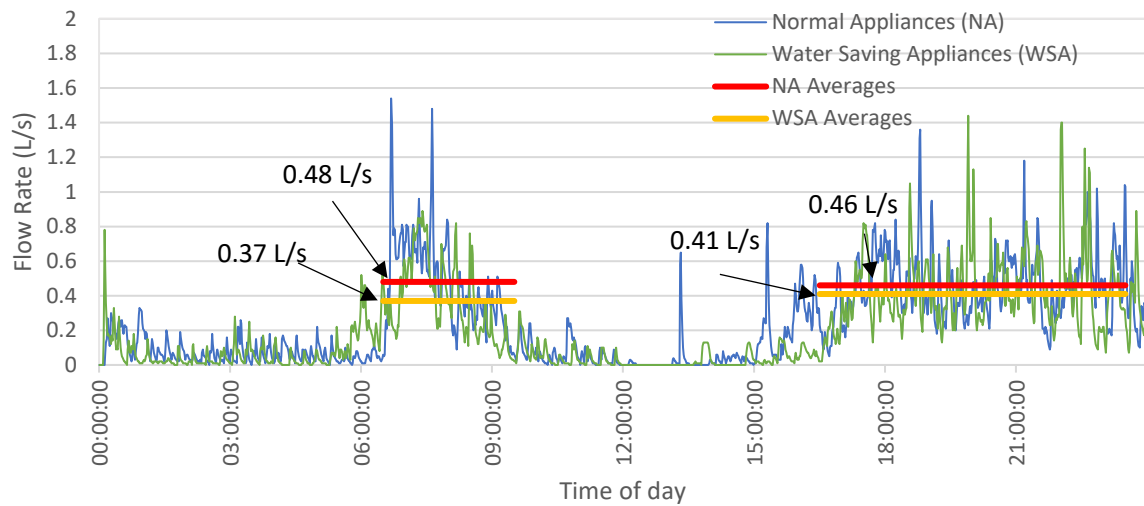


Figure 6.2-2- Flowrate of wastewater comparing normal household appliances and water saving household appliances.

A morning peak period of 6:30 AM to 9:30 AM and an evening peak period of 4:30 PM to 11:30 PM was chosen based on the data trends. As can be seen in Figure 6.2-2 the average flowrate over the morning period is 0.11 L s^{-1} lower on average using the water saving appliances. This confirms the idea that using water saving appliances will lead to a lower flowrate of water into the sewer system and therefore dilution should be reduced.

These averages were calculated for each of the 5 days that the simulation was run for and compared to check the reliability of a stochastic model. Figure 6.2-3 shows the average flowrate over the morning period, comparing the normal appliances with water-saving appliances. Error bars are also shown on Figure 6.2-3.

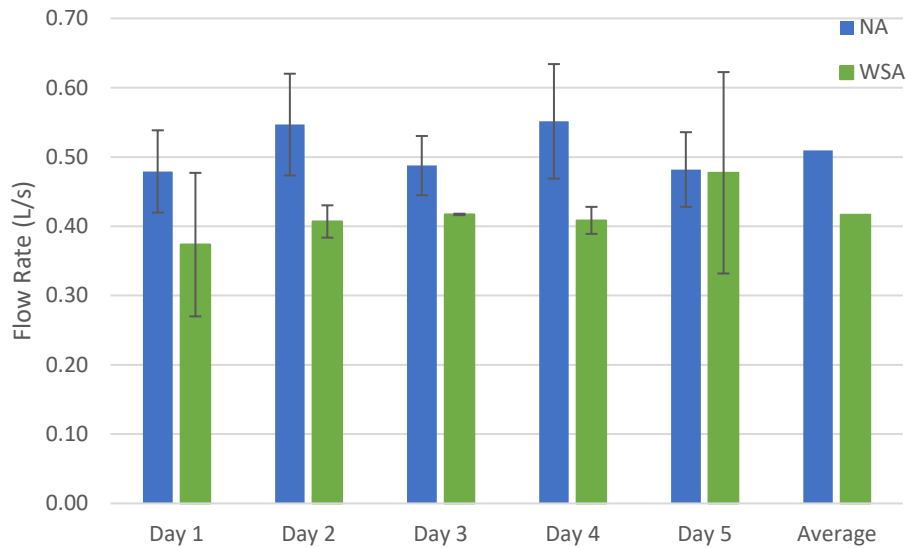


Figure 6.2-3- Average flowrate over the morning period for each day.

As can be seen on Figure 6.2-3 the stochastic model holds true for each day, where the water saving appliances give a lower flowrate of water into the sewer network when compared with the normal appliances. The average flowrate for the whole 5-day period for normal appliances is 0.09 L s^{-1} higher than for the water saving appliances. Each bar for days 1 to 5 also shows an error bar. This is because the flow rate for each day is different due to the random nature of the stochastic model. The SIMDEUM program gives random usage patterns to each household appliance which can mean, for example, on some days the toilet is flushed more frequently, which would lead to a higher flowrate into the sewer network. The trend does generally hold true, however, that the NA use more water than the WSA for days 1 to 4. On day 5 the average morning flowrate from the NA and the WSA is the same at around 0.48 L s^{-1} , which can be explained by the random nature of the model.

6.3- Simulation Results- Nutrient Concentration

In order to observe the effects of the decreased flow rate using WSA on the nutrient concentration in the wastewater, the concentration time series produced from SIMDEUM WW were linked to each house type in the SWMM sewer network along with the flow time series and the simulation was run for the same 5-day period. This was done for nitrogen, phosphorus, COD and SS concentrations. As an example, the results of the phosphorus concentration in the wastewater are displayed in this section. The simulation results for the other nutrients can be seen in the Appendix.

Figure 6.3-1 below shows the concentration of phosphorous at the outfall of the SWMM sewer network for the 5-day weekday period that the simulation was run for. As for the flowrate in Figure 6.2-1 the same diurnal pattern can be seen. The phosphorous concentration is higher when people are using the household appliances in the morning and evening periods, and phosphorus is being added to the wastewater system.

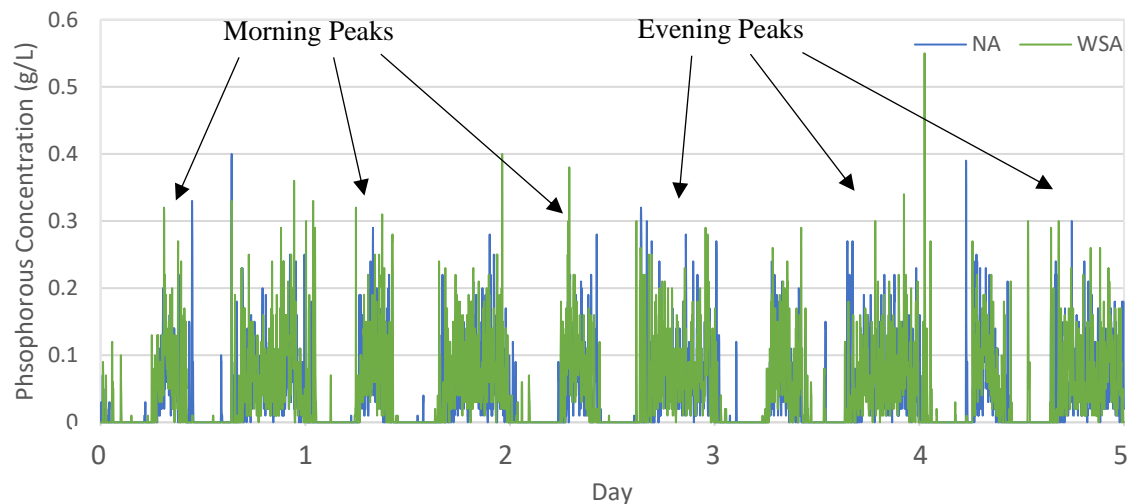


Figure 6.3-1- Wastewater phosphorous concentration at network outfall for a 5-day period.

The diurnal pattern can be clearly seen in Figure 6.3-1 with the morning peaks of phosphorous concentration, followed by very low phosphorus concentrations during the day when people tend to be away from home, and then a more widespread evening peak period where people are at home again and using water appliances such as the shower, and finally a very low concentration period when people are asleep and not using the water appliances before the next morning. Any peaks showing an influx of phosphorus in the wastewater during the night period could be explained by people going to the toilet during the night and then using soap to wash their hands afterwards, which adds phosphorus into the wastewater system and increases the concentration.

In order to see the difference in concentration between using the water saving appliances and normal appliances, a single day has been analysed in more depth, as can be seen in Figure 6.3-2.

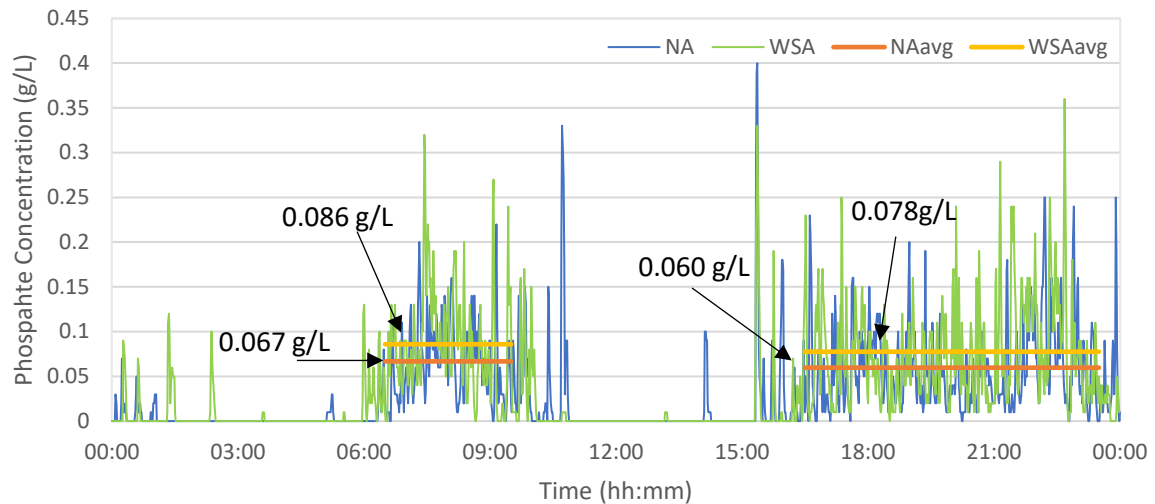


Figure 6.3-2 - Wastewater phosphorus concentration comparing normal household appliances and water saving household appliances.

Figure 6.3-2 shows the phosphorous concentration at the outfall for day 1 of the simulation period. The concentration profile for normal appliances and for water saving appliances are both shown with the averages of the morning and evening periods directly compared. As can be seen for the morning period the average phosphorous concentration is 0.019 g L^{-1} higher for the water saving appliances and is about 0.018 g L^{-1} higher in the evening period. This confirms the prediction that the lower the flowrate of water into the system, the less dilution there is and the higher the nutrient concentration. With a higher nutrient concentration, the water treatment and nutrient recovery process will be more effective. The phosphorous concentration can be seen to fluctuate late into the night after people tend to go to bed, this may be due to some household appliances such as dishwashers and washing machines being run at night with phosphorus containing detergents.

To check if this same trend holds true Figure 6.3-3 shows the average morning concentration for all 5 days of the simulation period, comparing the normal and water saving appliances.

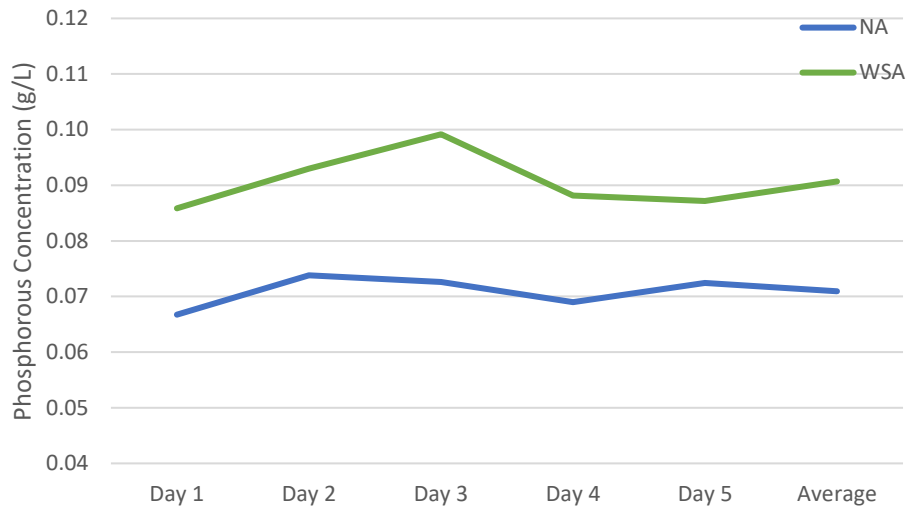


Figure 6.3-3 - Average phosphorous concentration over the morning period for each day.

As can be seen in Figure 6.3-3 the phosphorous concentration in the wastewater is consistently higher using the WSA compared to the NA. On average, the phosphorous concentration using the WSA is 0.02 g L^{-1} higher than with the NA, showing a 28% increase in the nutrient concentration of phosphorus. There is a degree of variance in the improvement from using the WSA. For example, for day 3 the concentration using WSA is 0.027 g L^{-1} higher, whereas for day 5 the concentration is only 0.014 g L^{-1} higher using the WSA. This confirms the randomness of the stochastic model used in this research.

The summary of the COD, SS and Nitrogen concentrations for NA and WSA can be seen in Table 6.3-1 below. The concentrations of each increases in the wastewater when using WSA compared to NA. This follows the expected trend as described for phosphorous. For COD and Phosphorous the biggest change appears to be over the morning period. For COD there is an average increase in concentration of 0.251 g L^{-1} over the morning period using the WSA, but only an increase of 0.118 g L^{-1} over the evening period. This could be due to the fact that the evening period is longer than the morning period and therefore more water is entering the sewer network and dilution is increased. As well as this, the average reduction in flow in the morning peak was 22% whereas for the evening peak, it was lower at 17%. This smaller reduction in flow over the evening peak means the dilution does not decrease by as much as it does for the morning peak, explaining the smaller increase in concentration for the evening period.

Table 6.3-1- Summary of COD, SS and N concentrations from the simulations.

		COD (g/L)		SS (g/L)		Nitrogen (g/L)	
		NA	WSA	NA	WSA	NA	WSA
Day 1	Morning	1.960	2.210	0.714	0.798	0.062	0.059
	Evening	1.608	1.793	0.657	0.770	0.053	0.054
Day 2	Morning	1.833	2.156	0.733	0.783	0.052	0.061
	Evening	1.815	2.043	0.659	0.742	0.047	0.055
Day 3	Morning	1.844	1.904	0.653	0.764	0.050	0.055
	Evening	1.839	1.849	0.656	0.711	0.050	0.058
Day 4	Morning	1.746	1.889	0.685	0.763	0.059	0.060
	Evening	1.843	1.840	0.624	0.768	0.051	0.059
Day 5	Morning	1.833	2.312	0.658	0.657	0.060	0.058
	Evening	1.790	1.962	0.640	0.732	0.055	0.053
Average	Morning	1.843	2.094	0.689	0.753	0.057	0.058
	Evening	1.779	1.897	0.647	0.744	0.051	0.056

Overall, the WSA in this project resulted in an average flow reduction of 18.2% for the morning period. This water use reduction resulted in increased average wastewater concentrations of Phosphorous, Nitrogen, COD and SS by 27.9%, 3.4%, 13.6% and 9.3% respectively. These percentages were comparatively low compared to the work of Bailey et al. (2020). This could be explained by the fact that in the research conducted by Bailey et al. (2020) five water saving scenarios were simulated, more than the 3 tested in this research. However, the results do follow the same relative trend.

Compared to the work of Pocernich and Litke (1997) the concentrations found in these simulations were much larger, for example the phosphorus concentration for the NA scenario was in the order of 7 times the values presented in the work of Pocernich and Litke (1997). One of the main reasons for this is due to the fact that there is not a lot of data presented for separated sewer network. Most previous data appears to be for combined sewer networks where the stormwater into the network leads to high levels of dilution. Therefore, it is clear from this work that using a separated sewer network drastically increases the nutrient concentrations and therefore will increase the effectiveness of nutrient recovery at treatment plants. Wastewater treatment plants will have to be extremely effective in removing most of the nutrients in order to reduce environmental impacts such as eutrophication caused by the increased nutrient concentrations. From the data presented here it is also clear that using WSA leads to higher concentrations in the wastewater which will also improve the effectiveness of the treatment plants.

7. Future work

The stochastic model developed in this research project shows promising diurnal patterns for wastewater flow and nutrient concentrations from households for a separated sewer network of a residential area. There are, however, a few stages in the development of the model that could be improved upon.

A potential change in the future would be to find better calibration data. This could be done by surveying a sample of the UK population in the specific area where the sewer network is being developed in order to account for local habits in terms of water use. A large portion of the data used in this project for the installation and consumption section of the Watershare Tool was obtained from demo files which had been calibrated to the Dutch scenario. In the future, further research could be done on the appliances and the time they are used for in the UK scenario, for example, how often people shower and for how long. This could be done by performing surveys on a sample of the UK population.

Another change that could be made in the future is to find more recent calibration data on the wastewater quality element of the model. Some of the nutrient discharge concentrations date back a few decades and with advancements in soaps and detergents it is likely that the pollutant qualities from these sources would have changed. With the availability of more time, further studies could be performed to find more recent information on nutrient qualities from household appliances. Another potential issue of the current form of SIMDEUM WW is that it uses average pollutant discharges per appliance. In reality each household appliance has the potential of producing a wide range of wastewater qualities, for example, people may use different detergents in clothes washing. To improve on the current form of the model it would be useful to be able to provide variable discharge qualities in SIMDEUM WW from each household appliance, improving on the stochastic model.

A further improvement that could be made to the SIMDEUM WW code is to integrate weekend days into the code. At the moment only weekdays have been simulated and weekday diurnal patterns have been shown. Weekend time budget data is available however, for example, when people wake up and how long they are away from home for. By adapting the SIMDEUM WW code the weekend demand patterns could also be converted into discharge profiles. A final

change that could be made in SIMDEUM WW is the usage pattern of the washing machine that sometimes produces errors when the code is run. This is an issue that also occurs when too many days are run in the code. Further investigation could be done to resolve this issue.

In this project, only 3 future water saving scenarios had been tested. The model does allow for more scenarios of water saving appliances and methods to be tested and this is something that could be looked into more in the future. For example, houses may use water saving dishwashers and aerated taps, which if the correct consumption data could be found, could be simulated in this model to observe the effects on wastewater flow and nutrient concentration. As well as this, there are likely to be changing in the future with advancements in household appliances, for example, more eco-friendly soaps become available, more houses have food grinders installed, and government regulations may change peoples' water use habits into the future, although this model allows for adaptations of these kinds.

8. Conclusion

A stochastic household wastewater discharge model has been developed in SIMDEUM and adapted through calibration methods to the UK population, in order to be related to the case study of a new housing development near Bristol, UK. Into the future, households will change to water saving appliances in order to conserve water in a more sustainable world, the effects of these water saving techniques on sewer networks and the wastewater treatment plants needs to be understood in order for the design of the most efficient sewer networks that lead to the best levels of nutrient recovery. Separated sewer networks are better for the future of sustainability due to the reduced levels of dilution and lower risk of CSOs causing damaging environmental impacts, and therefore the model developed in this research is for a separated residential sewer network, although the modelling tool, SWMM, does allow for the ability of rainfall being added in a combined sewer network. Using time budget data this model gives accurate results on the effects of water saving appliances on the flow rate and nutrient concentrations in the sewer network, following clear diurnal patterns.

Using SIMDEUM WW household discharge patterns could be paired up with nutrient discharge concentrations on a per use basis. The resulting nutrient discharge patterns could be implemented into the case study's hydraulic model to show the effects of water saving

appliances compared to normal household appliances. By using water saving toilets, water saving shower heads and waterless washing machines, the flow rate of wastewater into the sewer network was reduced by as much as 28.7% with an average reduction of 18.2% for the morning period. Both morning and evening periods saw flow reductions although the morning period often saw the largest decrease in flowrate using the water saving appliances.

Using the stochastic nutrient profiles for household discharge produced in SIMDEUM WW, the pollutant concentrations were obtained from simulations in SWMM. The simulations were run for Phosphorous, Nitrogen, COD and SS. The phosphorous concentration in the wastewater increased by as much as 36.6% using water saving appliances and increased by an average of 27.9% over the morning period. The concentrations for all other nutrients were also seen to increase with reduced flow and therefore dilution into the sewer system. This allowed for the assessment of the affect on nutrient recovery in water treatment plants from the implementation of water saving appliances in households. Due to the increased nutrient concentrations from the use of a separated network and water saving appliances, nutrient recovery would be more efficient, which is necessary for a more sustainable future, especially when natural resources such as phosphorus are becoming extremely depleted in the natural world.

Acknowledgements

I would like to thank Prof. Jan Hofman for continued support throughout this project, as well as his valuable advice, ideas and guidance. It has also been a pleasure working with Tendai Evans-Gavhure throughout this project, sharing ideas and supporting each other was a great help.

References

- Alcamo, J., T. Henrichs, and T. Rösch, (2000). World water in 2025. *Global modeling and scenario analysis for the World Commission on Water for the 21st Century*. [Online] Available from: <http://www.env-edu.gr/Documents/World%20Water%20in%202025.pdf> [Accessed 26/04/2021].
- Bailey, O., Arnot, T. C., Blokker, E. J. M., Kapelan, Z., Vreeburg, J., Hofman, J. A. M. H., (2019). Developing a stochastic sewer model to support sewer design under water conservation measures. *Journal of Hydrology*, 573: 908-917. DOI: <https://doi.org/10.1016/j.jhydrol.2019.04.013>.
- Bailey, O.; Zlatanovic, L.; van der Hoek, J.P.; Kapelan, Z.; Blokker, M.; Arnot, T.; Hofman, J., (2020) A Stochastic Model to Predict Flow, Nutrient and Temperature Changes in a Sewer under Water Conservation Scenarios. *Water* 2020, 12, 1187. DOI: <https://doi.org/10.3390/w12041187>
- Blokker, E.J.M., Vreeburg, J.H.G., van Dijk, J.C., (2010). Simulating residential water demand with a stochastic end-use model. *Water Resource, Planning and Managemeny*. 136 (1), 19–26. DOI: [https://doi.org/10.1061/\(ASCE\)WR.1943-5452.0000002](https://doi.org/10.1061/(ASCE)WR.1943-5452.0000002).
- Blokker, E.J.M., (2011). Stochastic Water Demand Modelling; *Hydraulics in Water Distribution Networks*. IWA Publishing, London.
- Brombach, H, Weiss, G and Fuchs, S., (2005). A new database on urban runoff pollution: comparison of separate and combined sewer systems. *Water Sci Technol.*, 51(2): 119–128.
- Bunce, J., Ndam, E., Ofiteru, I., Moore, A., Graham, D., (2018), A Review of Phosphorus Removal Technologies and Their Applicability to Small-Scale Domestic Wastewater Treatment Systems. DOI: <https://doi.org/10.3389/fenvs.2018.00008>.
- Burns, S., (2018). This Washing Machine Uses Beads to Clean Your Clothes, *Ever Widening Circles*. [Online] Available from: <https://everwideningcircles.com/2018/03/06/washing-machine-uses-beads-to-clean-clothes/> [Accessed 26/04/2021].
- Butler, D., Davies, J., (2004), *Urban Drainage*- Second Edition, Spon Press- Taylor & Francis Group, London and New York.
- Butler, D. and Parkinson, J., (1997) Towards sustainable urban drainage. *Water Science and Technology*, 35(9), 53–63.

- Carrillo, V., Fuentes, B., Gómez, G. et al., (2020) Characterization and recovery of phosphorus from wastewater by combined technologies. *Rev Environ Sci Biotechnol* 19, 389–418. DOI: <https://doi.org/10.1007/s11157-020-09533-1>
- Davis, J.A., Bursztynsky, T.A., (1980). Effects of water conservation on municipal wastewater treatment facilities, *Water Pollution Control Federation*, Vol. 52, pp. 730-739.
- DeZellar, J., Maier, W., (1980). Effects of water conservation on sanitary sewers and wastewater treatment plants, *Water Pollution Control Federation*, Vol. 52, pp. 76-88.
- Dixon, A., Butler, D., Fewkes, A., (1999). Water saving potential of domestic water reuse systems using greywater and rainwater in combination. DOI: [https://doi.org/10.1016/S0273-1223\(99\)00083-9](https://doi.org/10.1016/S0273-1223(99)00083-9)
- EPA.gov, (2021). United States Environmental Protection Agency, Storm Water Management Model (SWMM), Helps predict runoff quantity and quality from drainage systems. [Online] Available from: <https://www.epa.gov/water-research/storm-water-management-model-swmm> [Accessed 26/04/2021].
- Falkenmark, M., J, Lundqvist., and C, Widstrand., (1989). Macro-scale water scarcity requires micro-scale approaches, *Nat. Resour. Forum*, **13**, 258– 267. DOI: <https://doi.org/10.1111/j.1477-8947.1989.tb00348.x>.
- Feachem, R., Bradley, D., Garelick, H. and Mara, D. (1981). Health Aspects of Excreta and Sullage Management – *A State-of-the-Art Review*, *The World Bank*.
- Haddaway, A., (2015). Nutrient Recovery Technology Transforms World’s Largest Wastewater Treatment Plant- *Waterworld*. [Online] Available from: <https://www.waterworld.com/international/article/16193822> [Accessed 26/04/2021].
- Jorgensen, B., Graymore, M., O’Toole, K., (2009). Household water use behaviour: An integrated model. DOI: <https://doi.org/10.1016/j.jenvman.2009.08.009>.
- Larsen, T., Udert, K., Lienert, J., (2013). Source separation and decentralization for wastewater management. *IWA Publishing*.
- Liu, J., Yang, H., Gosling, S. et al. (2017). Water scarcity assessments in the past, present, and future. DOI: <https://doi.org/10.1002/2016EF000518>
- Morse, K., Lester, N. and Perry, R. (1993). The Economic and Environmental Impact of Phosphorus Removal from Wastewater in the European Community, *Selper Publications*.

Mulder, C., (2014). Impact of intrinsic and extrinsic parameters on the oxygen kinetic parameters of ammonia and nitrite oxidizing bacteria. DOI:10.13140/RG.2.2.11347.17444

NYC.gov, (2021). Combined Sewer Overflows, *NYC Environmental Protection*. [Online] Available from: <https://www1.nyc.gov/site/dep/water/combined-sewer-overflows.page> [Accessed 26/04/2021].

Parkinson, J., Schütze, M., Butler, D., (2005). Modelling the impacts of domestic water conservation on the sustainability of the urban sewerage system. *Chartered Institution. Water Environmental Management*. 19 (1), 49–56.

Penn, R., Schütze, M., Friedler, E., (2014). Assessment of the effects of greywater reuse on gross solids movement in sewer systems. *Water Science Technology* 69 (1), 99–105. DOI:[https:// doi.org/10.2166/wst.2013.555](https://doi.org/10.2166/wst.2013.555).

Pieterse-Quirijns, E.J., Agudelo-Vera, C.M., Blokker, E.J.M., (2012). Modelling sustainability in water supply and drainage with SIMDEUM®, CIBW062 Symposium.

Pocernich, M., Litke, D., (2007). Nutrient Concentrations in Wastewater Treatment Plant Effluents, South Platte River Basin. DOI: <https://doi.org/10.1111/j.1752-1688.1997.tb04096.x>

Shokory, J. and Rabanizada, E., (2020). Sustainable household water-saving and demand management options for Kabul City. [Online], Available from: <https://iopscience.iop.org/article/10.1088/1755-1315/511/1/012003/pdf> [Accessed 26/04/2021].

Sullivan, O., Gershuny, J., (2020). United Kingdom Time Use Survey, 2014-2015, [data collection], UK Data Service, DOI: <http://doi.org/10.5255/UKDA-SN-8128-1>

The Hangar District, (2021). The Homes, Houses and Apartments at Brabazon Brochure.

UN, (2015). WWAP (United Nations World Water Assessment Programme), *The United Nations World Water Development Report 2015: Water for a Sustainable World*. Paris, UNESCO.

United Nations, (1992). United Nations Conference in environment and Development, Rio de Janeiro, Brazil, 3-14 June 1992. [Online] Available from: <https://www.un.org/en/conferences/environment/rio1992> [Accessed 26/04/2021].

Wageningen, (2021). Recovering nutrients from wastewater. [Online] Available from: <https://www.wur.nl/en/show/Recovering-nutrients-from-waste-water.htm> [Accessed 26/04/2021].

Watershare, (2021). Water-Use Info Tool. [Online] Available from: <https://www.watershare.eu/tool/water-use-info/>. [Accessed 26/04/2021].

Waterwise (2016). WWT Water Consumption, PR19 Challenge Report #5. [Online] Available from: <https://waterwise.org.uk/wp-content/uploads/2019/10/WWT-Report-.pdf> [Accessed 26/04/2021].

Willis, Rachelle, Stewart et al. (2006). Revealing the impact of socio-demographic factors and efficient devices on end use water consumption: case of Gold Coast, Australia. [Online] Available from: <http://hdl.handle.net/10072/27300> [Accessed 26/04/2021].

World Economic Forum, (2015). Insight Report, Global Risk 2015, 10th Edition. [Online] Available from: http://www3.weforum.org/docs/WEF_Global_Risks_2015_Report15.pdf [Accessed 26/04/2021].

World Economic Forum, (2021). Insight Report, Global Risk 2015, 16th Edition. [Online] Available from: http://www3.weforum.org/docs/WEF_The_Global_Risks_Report_2021.pdf [Accessed 26/04/2021].

WTE.Ltd (2021). Wastewater Production In The UK Home, *Wastewater Produced In The Home*. [Online] Available from: <https://www.wte-ltd.co.uk/wastewater-amounts-in-the-home.html> [Accessed 26/04/2021].

Verstraete, W., and Vlaeminck, S., (2011). ZeroWasteWater: short-cycling of wastewater resources for sustainable cities of the future, *International Journal of Sustainable Development & World Ecology*, 18:3, 253-264, DOI: 10.1080/13504509.2011.570804

Appendix

	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	Formula
36	serial	strata	psu	pnum	daynum	HhOut	IndOut	DMFlag	IMonth	IYear	DVAge	DayNum_DiaryDay	DPday	DiaryDate_Act	DiaryDay_Act	DiaryDateDiff	dmonth	dyear	ddayw
37	11011202	110	117	1	1	210	11	2	12	2014	48	1	12/11/2014	12/11/2014	5	0	12	2014	1
38	11011202	110	117	1	2	210	11	2	12	2014	48	2	12/14/2014	12/14/2014	1	0	12	2014	3
39	11011202	110	117	4	1	210	11	3	12	2014	13	1	12/11/2014	12/11/2014	5	0	12	2014	1
40	11011202	110	117	4	2	210	11	3	12	2014	13	2	12/14/2014	12/14/2014	1	0	12	2014	3
41	11011203	110	117	1	1	210	11	2	12	2014	75	1	12/07/2014	12/07/2014	1	0	12	2014	3
42	11011203	110	117	1	2	210	11	2	12	2014	75	2	12/09/2014	12/09/2014	3	0	12	2014	1
43	11011207	110	117	1	1	110	11	1	12	2014	68	1	12/03/2014	12/03/2014	4	0	12	2014	1
44	11011207	110	117	1	2	110	11	1	12	2014	68	2	12/06/2014	12/06/2014	7	0	12	2014	2
45	11011207	110	117	2	1	110	11	1	12	2014	74	1	12/03/2014	12/03/2014	4	0	12	2014	1
46	11011207	110	117	2	2	110	11	1	12	2014	74	2	12/06/2014	12/06/2014	7	0	12	2014	2
47	11011209	110	117	1	1	110	11	1	12	2014	69	1	12/03/2014	12/03/2014	4	0	12	2014	1
48	11011209	110	117	1	2	110	11	1	12	2014	69	2	12/07/2014	12/07/2014	1	0	12	2014	3
49	11011209	110	117	2	1	110	11	1	12	2014	60	1	12/03/2014	12/03/2014	4	0	12	2014	1
50	11011209	110	117	2	2	110	11	1	12	2014	60	2	12/07/2014	12/07/2014	1	0	12	2014	3
51	11011210	110	117	1	1	110	11	1	12	2014	29	1	12/11/2014	12/11/2014	5	0	12	2014	1
52	11011210	110	117	1	2	110	11	1	12	2014	29	2	12/13/2014	12/13/2014	7	0	12	2014	2
53	11011210	110	117	2	1	110	11	1	12	2014	36	1	12/11/2014	12/11/2014	5	0	12	2014	1
54	11011210	110	117	2	2	110	11	1	12	2014	36	2	12/13/2014	12/13/2014	7	0	12	2014	2
55	11011211	110	117	1	1	110	11	1	12	2014	69	1	12/14/2014	12/14/2014	1	0	12	2014	3
56	11011211	110	117	1	2	110	11	1	12	2014	69	2	12/15/2014	12/15/2014	2	0	12	2014	1
57	11011211	110	117	2	1	110	11	1	12	2014	70	1	12/14/2014	12/14/2014	1	0	12	2014	3
58	11011211	110	117	2	2	110	11	1	12	2014	70	2	12/15/2014	12/15/2014	2	0	12	2014	1
59	11011212	110	117	1	1	110	11	1	1	2015	41	1	01/10/2015	01/10/2015	7	0	1	2015	2
60	11011212	110	117	1	2	110	11	1	1	2015	41	2	01/12/2015	01/12/2015	2	0	1	2015	1
61	11011212	110	117	2	1	110	11	1	1	2015	44	1	01/10/2015	01/10/2015	7	0	1	2015	2
62	11011212	110	117	2	2	110	11	1	1	2015	44	2	01/12/2015	01/12/2015	2	0	1	2015	1

Figure A-1-Extract from Survey Data.

Pos. = 32 Variable = act1_1 Variable label = Primary activity: 04:00-04:10
This variable is *numeric*, the SPSS measurement level is *SCALE*
Value label information for act1_1
Value = 0.0 Label = Unspecified personal care
Value = 5120.0 Label = Visiting and receiving visitors
Value = 7170.0 Label = Correspondence
Value = 4100.0 Label = Unspecified organisational work
Value = 6149.0 Label = Other specified ball games
Value = 6150.0 Label = Gymnastics
Value = 5292.0 Label = Visiting a wildlife site
Value = 5130.0 Label = Celebrations
Value = 4110.0 Label = Work for an organisation
Value = 6160.0 Label = Fitness
Value = 8210.0 Label = Unspecified TV video or DVD watching
Value = 8211.0 Label = Watching a film on TV
Value = 5140.0 Label = Telephone conversation
Value = 4270.0 Label = Unspecified childcare as help to other households
Value = 7190.0 Label = Other specified or unspecified arts and hobbies
Value = 4120.0 Label = Volunteer work through an organisation
Value = 6170.0 Label = Unspecified water sports
Value = 8219.0 Label = Other specified TV watching
Value = 3100.0 Label = Unspecified food management
Value = 8221.0 Label = Watching a film on video
Value = 8222.0 Label = Watching sport on video
Value = 6179.0 Label = Other specified water sports
Value = 8229.0 Label = Other specified video watching
Value = 3110.0 Label = Food preparation and baking
Value = 3250.0 Label = Disposal of waste
Value = 6190.0 Label = Other specified physical exercise
Value = 4275.0 Label = Physical care and supervision of own child as help to other household
Value = 2100.0 Label = Study: Unspecified activities related to school or university
Value = 6200.0 Label = Unspecified productive exercise
Value = 3130.0 Label = Dish washing
Value = 2110.0 Label = Study: Classes and lectures
Value = 7231.0 Label = Information searching on the internet
Value = 6210.0 Label = Hunting and fishing
Value = 3140.0 Label = Preserving
Value = 5190.0 Label = Other specified social life

Figure A-2- Example section of the key for the UK data.

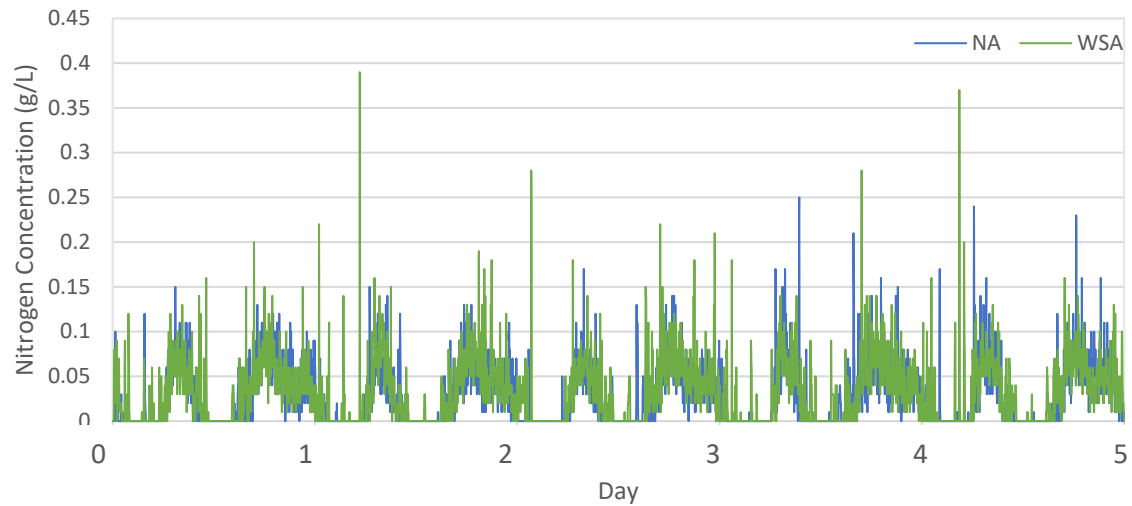


Figure A-2- 5 day simulation results of Nitrogen concentration at outfall.

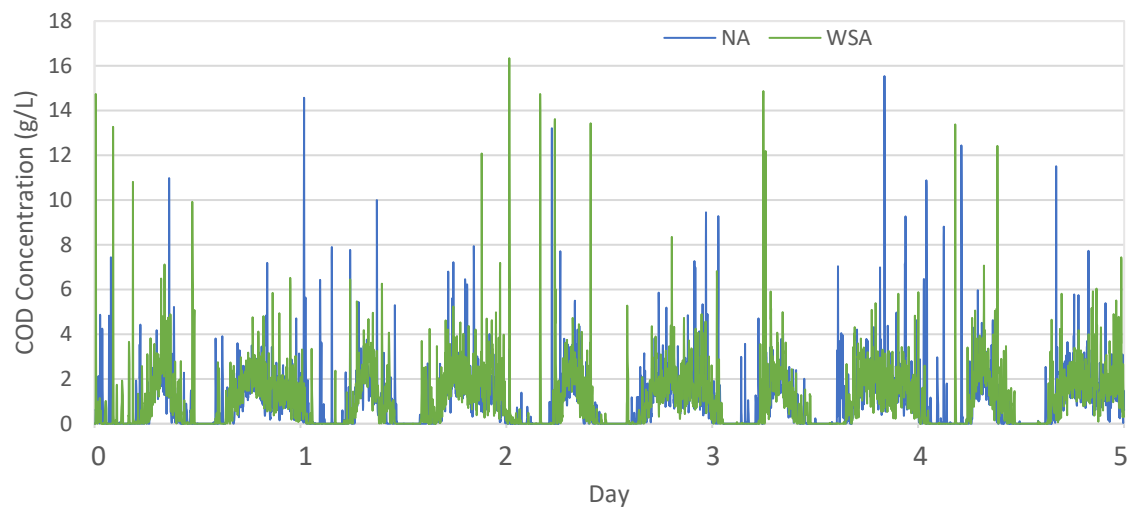


Figure A-5- 5 day simulation results of COD concentration at outfall.

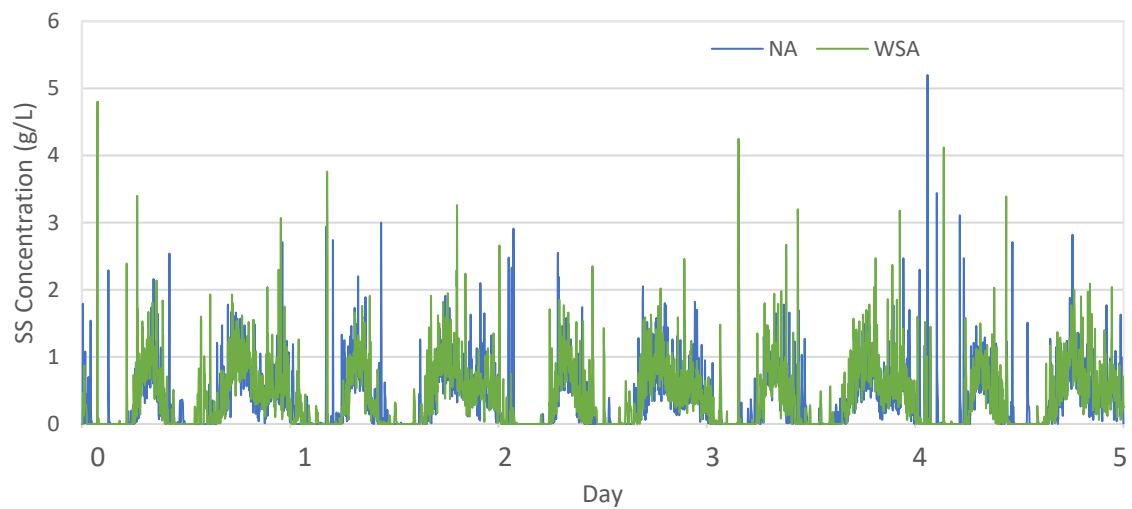


Figure A-6- 5 day simulation results of SS concentration at outfall.