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Sewer Systems of the Future: Developing a stochastic sewer model to support design of sustainable wastewater systems

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‘Better to start in the evening than not at all’

James Duthie, I cycled into the Arctic Circle (1951)

Abstract

Global population growth, urbanisation and the threat of climate change are urging us to live more sustainably. This drive for sustainability extends to the urban water cycle. Wastewater systems were originally designed to protect human health but, in the transition to a more sustainable way of life, they could serve a greater purpose into the future. The water cycle is facing changes into the future that conserve water, improve efficiency and maximise the recovery and reuse of natural resources. This thesis sort to explore the effects of water conservation on the sewer system with a view to improve the sustainability of the wastewater system.

Initially, a hydraulic sewer model was developed to incorporate stochastic discharge patterns into a sewer network model. The stochastic sewer model integrated the stochastic water demand model SIMDEUM® with the InfoWorks® ICM (Sewer Edition) hydraulic model and software. The sewer model was tested and validated using sewer network data from real catchments in the Wessex Water area of the UK. This stochastic model, in which every household discharges a unique flow into the sewer, was compared to the continuous, deterministic model and deemed to be superior in representing the real system. The validated model performed well to predict sewer flow in the study catchment and was therefore used to study the impact of certain levels of water conservation. This early study showed how the diurnal wastewater pattern would be effected by up to 75% reduction in water use. It was found that overnight and daytime flow was reduced by up to 80% whereas evening flows remained largely similar. Extended stagnation times were observed in the street scale pipes (150 mm) in the low water use scenario.

The development of the model progressed by including wastewater pollutant loadings that were linked to specific household appliances, using the wastewater extension of SIMDEUM®, SIMDEUM WW®. By incorporating appliance-specific pollutographs into the stochastic model it was possible to simulate the effects of various water saving scenarios on wastewater concentration. The increasing concentration of wastewater is important for resource recovery and thus five future scenarios, developed by Artesia Consulting (on OFWAT's behalf), were tested for their effect on flow, wastewater temperature and concentration of COD, TPH and TKN. These scenarios outlined how commercial and political factors may change water use in future. The scenario testing showed that a 15-60% reduction in domestic water use resulted in a 1-48% drop in the morning peak flow. The water use reductions increased wastewater concentrations of COD, TKN and TPH by 55-180%, 19-116% and 30-206% respectively. As such, this model had proved it could produce some useful outcomes to address future water use but the wastewater quality aspects were based purely on

literature and lacked the necessary sewer measurements to ensure the model prediction was robust.

To investigate the model prediction further, the flow and quality model was applied to a sewer network in Amsterdam, The Netherlands. A week-long wastewater monitoring campaign was conducted in order to gain sufficient data on wastewater quality to validate the model's outputs. Wastewater concentrations of TSS, COD, TKN, TPH were sampled on an hourly basis and wastewater temperature was recorded every 3-5 minutes. The results obtained from this campaign showed that the model predicted the mass flow of pollutants well but, due to the current lack of a time-varying solids transport model within InfoWorks® ICM, the prediction for wastewater concentration parameters was less good. Aside from this, the model was deemed capable of analysing the effects of three different water conservation strategies (greywater reuse, rainwater harvesting and installation of water-saving appliances) on flow, nutrient concentrations, and temperature in sewer networks. Resulting from this final scenario analysis, through a 62% reduction in sewer flow, an increase in concentration was achieved of COD, TKN and TPH by up to 111%, 84% and 75% respectively, offering more favourable conditions for nutrient recovery.

Finally, the concept of integrating this knowledge into the water industry was discussed. The strengths and weaknesses of this model were addressed and analysed as to how the water industry could best utilise the outputs of the model to improve sustainability in the water cycle.

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Conference contributions

Conference papers

Bailey O., Hofman J.A.M.H., Arnot T.C., Kapelan Z., Blokker M., Vreeburg J. (2019) Developing a Stochastic Sewer Input Model to Support Sewer Design Under Water Conservation Measures. In: Mannina G. (eds) New Trends in Urban Drainage Modelling. UDM 2018. Green Energy and Technology. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-99867-1_13.

Oral presentations

9th International Conference on Sewer Processes & Networks (Aalborg, Demark), 27-30th August 2019: Predicting Impacts of Water Conservation with a Stochastic Sewer Model (Olivia Bailey, Jan Hofman, Tom Arnot, Mirjam Blokker Zoran Kapelan, Jan Vreeburg)

Efficient 2019 (Manila, Philippines), 13-16th January 2019: Developing a stochastic sewer model to support sewer design under water conservation measures (Olivia Bailey, Jan Hofman, Tom Arnot, Mirjam Blokker Zoran Kapelan, Jan Vreeburg)

Urban Drainage Modelling 2018 (Palermo, Italy), 23-26th September 2018: Developing a stochastic sewer input model to support sewer design under water conservation measures (Olivia Bailey, Jan Hofman, Tom Arnot, Mirjam Blokker Zoran Kapelan, Jan Vreeburg)

19th UK-IWA Young Water Professionals Conference (Cranfield, UK), 16-18th April 2018: Developing a stochastic sewer input model to support sewer design under water conservation measures (Olivia Bailey, Jan Hofman, Tom Arnot, Mirjam Blokker Zoran Kapelan, Jan Vreeburg)

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Co-authored publications

Zlatanović, L., Bailey O., Hofman J., Vreeburg J., Blokker M. & van der Hoek, J. P. (2019) Towards circular urban water cycles: Resource recovery based urban water transport systems. Abstract from 3rd IWA Resource Recovery Conference, Venice, Italy

Zlatanović, L., Bailey O., Hofman J., Vreeburg J., Blokker M. & van der Hoek, J. P. (2019) Towards circular urban water cycles. Abstract from AIWW Conference, Amsterdam, Netherlands

Symbols and abbreviations

Symbols

d	Flow depth (m)
D	Pipe diameter (m)
d/D	Proportional depth (m/m)
u	Velocity of flow in the sewer (m s^{-1})
r	Hydraulic mean depth of flow (m) (=a/p)
a	Cross section area of flow (m^2)
p	Wetted perimeter (m)
n	Mannings coefficient (depends upon the type of the channel surface)
s	Hydraulic gradient, equal to invert slope for uniform flows (m/m)
v	Kinematic viscosity (m^2 s^{-1})
k	Wall/pipe roughness (m)
g	Gravitational acceleration (m s^{-2})
A	Cross sectional area (m^2)
B	Water surface width (m)
S_o	Bed slope (m/m)
S_f	Friction slope (m/m)
x, y	Longitudinal, vertical coordinate
Q	Volumetric flowrate (m^3 s)
X_i	Number of households with water use inside interval,i
M_J	Mass of suspended sediment or dissolved pollutant in node J (kg)
Q_i	Flow into node J from link i (m^3 s^{-1})
t	Time (s)
C_A	Concentration of pollutant A in the tank (kg m^{-3})
$C_{A,in}$	Concentration of pollutant A into the tank (kg m^{-3})
$C_{A,o}$	Initial concentration of pollutant A (kg m^{-3})
V	Tank volume (m^3)
$V_{[\tau_n,\tau_{n+1}]}$	Volume entering the tank between level sensor readings (m^3)
PC	Pumping capacity (m^3 s^{-1})
LS	Tank level (m)
A	Tank area (m^2)
$S1, S2$	Level sensors
x_{obs}	Observed parameter
x_{sim}	Simulated parameter
$\bar{x}, \bar{y}$	Sample mean of parameters x, y
c_i	Cconcentration in the flow into node J from link i (kg m^{-3})
M_{sJ}	Additional mass entering node J from external sources (kg)
Q_o	Flow from node J to link o (m^3 s^{-1})
c_o	concentration in the flow from node J to link o (kg m^{-3})
F_a	Mass flow through the face due to advection (kg s^{-1})
F_m	Volumetric flow through the face (m^3 s^{-1})
c_{upwind}	c_l if volumetric flow goes from left to right element, c_r otherwise (kg m^{-3})
c_l	Determinant concentration in left element (kg m^{-3})
c_r	Determinant concentration in right element (kg m^{-3})

Abbreviations

CSO	Combined sewer overflow
WWTP	Wastewater treatment plant
SIMDEUM®	SIMulation of water Demand, and End-Use Model
SIMDEUM WW®	SIMulation of water Demand, and End-Use Model (Wastewater)
UKWIR	UK Water Industry Research Ltd.
EPA SWMM	Stormwater management model (EPA - United States Environmental Protection Agency)
IUWM	Integrated urban water management
OCED	Organisation for Economic Co-operation and Development
DEFRA	Department for Environment, Food and Rural Affairs
COD	Chemical oxygen demand
TSS	Total suspended solids
TPH	Total phosphorus
TKN	Total Kjeldahl nitrogen
GWR	Greywater reuse
RWH	Rainwater harvesting
SUDS	Sustainable urban drainage systems
CHP	Combined heat and power
DWDS	Drinking water distribution system
OFWAT	UK Water Services Regulation authority
AWS	All Water Services
WISE CDT	Water informatics, science and engineering (Centre for Doctoral Training)
EPSRC	Engineering and Physical Sciences Research Council
NUWTS	New urban water transport systems
RMSE	Root mean squared error
NSE	Nash-Sutcliffe efficiency
R	Correlation coefficient
BrTap	Bathroom tap
Dw	Dishwasher
Ktap	Kitchen tap
OsTap	Outside tap
Wc	Toilet
Wm	Washing machine

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Introduction

Into the future, water sources are expected to become increasingly scarce and conserving household water use is becoming an increasingly important topic. There is also a trend towards considering wastewater less as a waste and more as a resource, promoting the recovery of nutrients and energy from sewage. This thesis sets out the need to better understand the effect that future water use scenarios have on sewerage infrastructure and the role these scenarios play in increasing recovery of resources. A review of relevant literature revealed that sewer models developed to date have been largely deterministic, however, to assess future, unseen scenarios it is important to develop a model based in probabilistic data. The aim of this thesis emerged, therefore, to develop a stochastic sewer model that can be used to simulate and observe the changes to wastewater flow and quality that could arise from future water use. This was with a view to improve sustainability within the urban water cycle.

To achieve the above aim, the core objectives of the project were defined as follows:

1. Integrate stochastic wastewater discharge patterns into a sewer network model to produce a sewer model that includes unique household discharges that are linked to specific appliances.
2. Define wastewater quality profiles for typical household water-using appliances and generate appliance-specific wastewater discharge profiles. This wastewater discharge information will be included as an input to the network model to predict time-varying wastewater quality through the sewer.
3. Calibrate and validate the hydraulic and wastewater quality models using data collection from case study networks.
4. Test future water use scenarios using the sewer model to predict changes to flow and wastewater quality, with a view to indicate changes to sewerage conditions e.g. solids transport, wastewater concentration, hydraulic and organic loading on the system.
5. Reflect on modelling outcomes to provide recommendations and implications of water conservation on sewer network design.

The thesis is set out in six chapters. The first chapter details a review of relevant literature that was used to inform the thesis aims and objectives. The following three results chapters have been published in scientific journals and have been presented here in line with the alternative thesis format as required by the University of Bath (Appendix 6A of the “Specifications for Higher Degree Theses and Portfolios). The first results chapter (Chapter 2) outlines the development and validation of a hydraulic model and shows some preliminary testing of the model using a UK-based case study.

The second results chapter (Chapter 3) describes the incorporation of wastewater quality into the aforementioned model and further tests the model using future scenarios to indicate impacts on wastewater flow, concentration and temperature. The final results chapter (Chapter 4) shows the application of the model within a Dutch case study and details a wastewater quality monitoring campaign that was carried out to further validate the model. Chapter 5 reflects on the model displayed in this thesis and provides recommendations for, and the implications of, using this work in sewer network design. Finally, Chapter 6 outlines the key conclusions of this thesis and proposes some lines for future work.

Chapter 1

Literature review

1.1 Context

By 2050, 50% of humans will live in areas of severe water stress (OECD, 2012). Population growth, climate change and urbanisation all play their part in this risk to water security, increasing the pressure on us to look for novel ways of doing more with less and conserving what we have. Wastewater offers the potential to recover many resources, including energy and nutrients, without depleting the world's non-renewable resources. For example, recovery of phosphorous from sewage sludge could meet up to 20% of the global requirement (Cieślik and Konieczka, 2017). However, the extent of dilution currently present in our wastewater system limits the effectiveness of treatment and resource recovery. Restricting the water that enters the sewer system could vastly improve efficiency of the process (Verstraete and Vlaeminck, 2011).

Sewage systems have been protecting human health and built infrastructure for hundreds of years but sustainability has often been overlooked. 96% of the UK population are connected to the 418,082 km sewer system (Combined Services Ltd., 2016; DEFRA, 2002). Combined drainage of stormwater and wastewater is one reason for the dilution of wastewater and can lead to networks being vastly oversized for the transport of domestic flows. Since the 50's, transition from combined to separate sewers has been taking effect, and now, around half the population connect to a separated network. This idea has become popular as we begin to design our urban landscapes in a more sensitive and efficient way. In a recent study by the World Bank (Hutton and Varughese, 2016), it was found that the capital investments required to achieve SDG6 (ensure availability and sustainable management of water and sanitation for all) amount to about three times the current investment levels ($150-250 billion per year, between 2015-2029). 70% of the required investment needed to achieve the SDGs accounts for urban areas. It is therefore apparent that major investment is still needed in global water infrastructure and a more efficient, sustainable sewer design would help reduce those costs.

Reducing domestic water use has been gathering interest for reasons of water security and sustainability but also to relieve pressure of urbanisation on existing networks by minimising the impact of new connections, extending the capacity of existing systems. It is important to understand how these demands on sewage systems will change in the future to maximise the sustainability of the urban water cycle.

1.2 An introduction to urban sewerage systems

1.2.1 The urban water cycle

Urban drainage systems have evolved to safely transport wastewater and stormwater away from built-up areas in order to protect human health and infrastructure. In the past, sewer systems were built to transport both domestic wastewater and stormwater together in the same pipe, these are called combined systems. Combined sewers (carrying both stormwater and wastewater) are commonly designed to drain peak rainfall, which leads to hugely oversized pipes for domestic wastewater flow. Additionally, during periods of heavy rain, combined sewers can overflow (CSO) into a nearby water body which can be damaging for ecosystems. Nowadays, sewers are designed to keep the two waters separate (separated sewers) although many previously built combined sewers remain in the UK.

Figure 1.2-1 shows a typical urban water cycle with a combined sewer network. Sanitary waste is coupled with rainwater through both direct inflow and infiltration from groundwater. During periods of heavy rain, combined sewers could overflow, via a CSO, into a nearby water body. Alternatively, water is taken to a wastewater treatment plant (WWTP), treated and then discharged into a nearby watercourse.

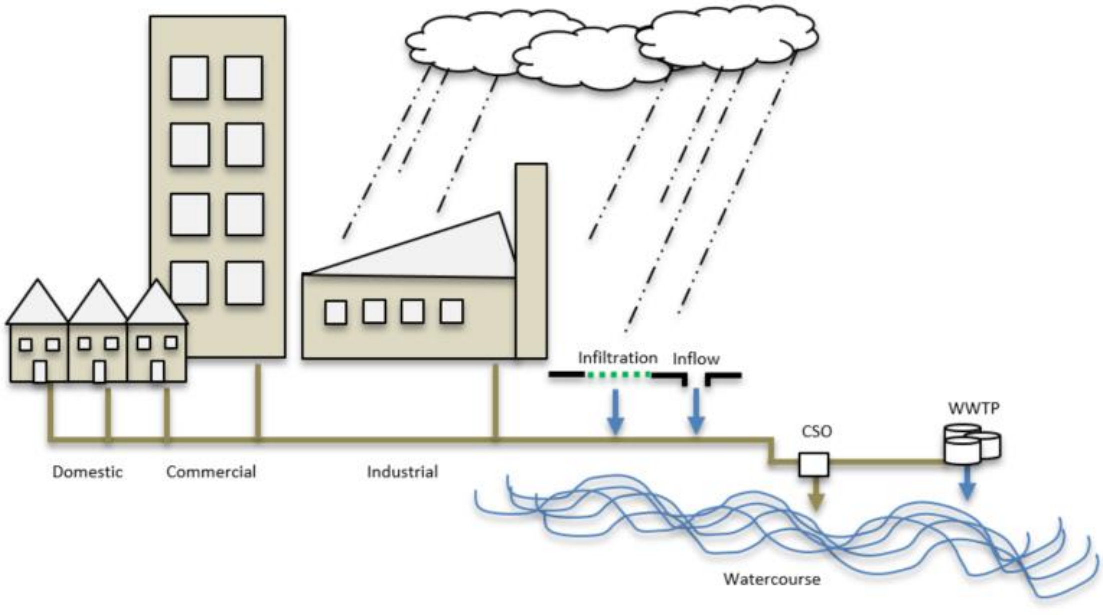

Figure 1.2-1. Outline of a combined urban wastewater network

1.2.2 Typical sewer system design

Combined sewers are sized based on rainfall intensities and the permeability of the catchment whereas the size of separated (foul) systems depends on the distribution of the population and the rate of water use (Read, 2004). This implies that combined sewers require much larger pipes than foul sewers and are thus grossly oversized for transporting dry weather flow (DWF). In addition to the larger pipes, combined drainage allows dilution of domestic wastewater and can introduce pollutants (e.g. heavy metals) that diminish the potential for resource recovery (Libralato et al, 2012; Roefs et al, 2016). A separated system can mean optimised designs for both wastewater and stormwater drainage. The Manning's formula is most commonly used for design of sewers. Where the velocity of flow through sewers can be determined using the relationship shown in equation 1.2-1.

$$u = \frac{1}{n}\, r^{2/3}\, s^{1/2} \tag{1.2-1}$$

Where,
u = Velocity of flow in the sewer (m s^{-1})
r = Hydraulic mean depth of flow (m) (=a/p)
a = Cross section area of flow (m^2)
p = Wetted perimeter (m)
n = Mannings coefficient (depends upon the type of the channel surface)
s = Hydraulic gradient, equal to invert slope for uniform flows (m/m)

However in the design of circular channels it is preferable to use the Colebrook-White formula, shown in equation 1.2-2. Some typical values for pipe roughness used in this equation are displayed in Table 1.2-1.

$$u = \left[-2\log\left(\frac{2.51\,v}{D\sqrt{2gDs}}\right) + \frac{k/D}{3.71}\right]\sqrt{2gDs} \tag{1.2-2}$$

Where,
u = velocity of flow in the sewer (m s^{-1})
D = diameter of pipe (m)
s = hydraulic gradient (m/m)
v = kinematic viscosity (m^2 s^{-1})
k = wall roughness (m)

Table 1.2-1. Typical pipe roughness (k) (Butler and Davies, 2011)

Pipe material	k range (mm)	
	New	Old
Clay	0.03-0.15	0.3-3.0
Polymers	0.03-0.06	0.15-1.50
Concrete	0.06-1.50	1.5-6.0
Brickwork	0.6-6.0	3.0-15.0

The current UK building regulations suggest that sewer design ensures pipes run less than 0.75 proportional depth (d/D) and at a minimum velocity of 0.75-1 m s^{-1} during times of peak flow (Butler and Davies, 2011; WRc, 2012). This is to provide adequate ventilation and ensure that sewers are self-cleaning. These criteria derive from lab tests that suggested 1-2.5 N m^{-2} was necessary to transport synthetic sediment, in field studies it was found that only 1 N m^{-2} was necessary (Arthur et al., 1999; Butler and Davies, 2011). Figure 1.2-2 outlines how the self-cleaning velocity varies for specific sewer conditions and size. Recommended pipe sizes in the upper sewer reaches should be at least 100 mm (<10 properties connected) or 150 mm (>10 properties connected) at minimum inclines of 1:100 and 1:150 respectively (BS-EN-12056, 2000; Department for Communities and Local Government, 2015). In practice, pipe diameters and gradients are manipulated to provide the best design that meets local requirements. Various charts are available in order to predict flow conditions for a given design criteria; Table 1.2-2 provides some example pipe systems that would operate at self-cleaning velocity.

Table 1.2-2. Example design requirements to reach self-cleaning velocity (derived from the Butler-Pinkerton design charts (Butler et al., 2003b))

Diameter (mm)	k (mm)	d/D	Slope	Velocity (m s^{-1})	Flowrate (L s^{-1})
150	0.6	0.75	1:100	1.13	16
225	0.6	0.75	1:100	1.47	47
375	0.6	0.75	1:100	2.05	180

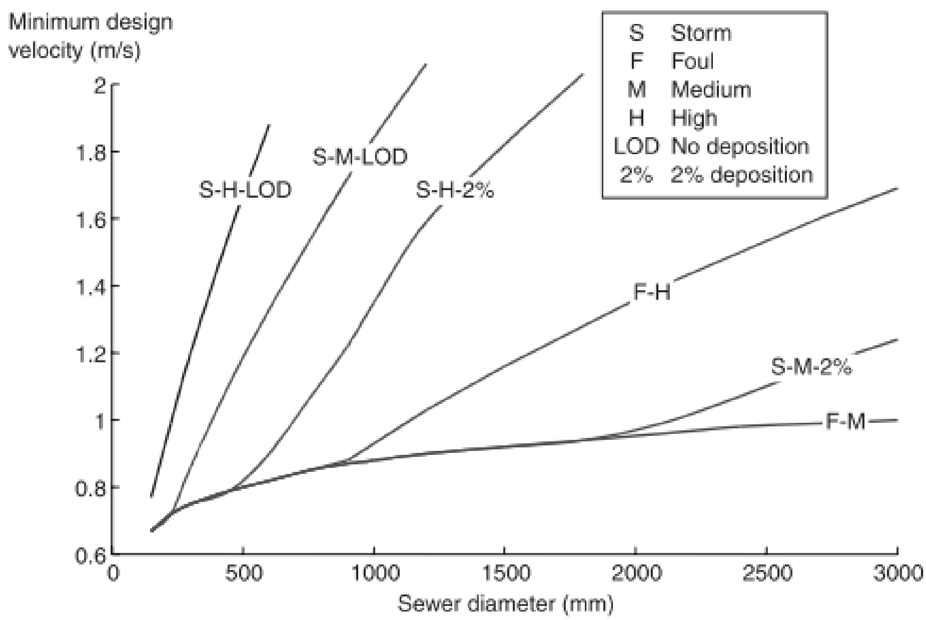

Figure 1.2-2. Minimum design velocity to ensure self-cleaning for flow with medium and high sediment load in foul and storm drains (Butler and Davies, 2011)

Table 1.2-3 indicates the typical pipe diameters and materials used in UK sewerage. Critical sewers are those that are considered to be very important to maintain i.e. those that could cause significant damage if compromised.

Table 1.2-3. Sewer size and material distribution the UK (Butler and Davies, 2011)

Pipe diameter (mm)	All sewers (%)	Critical sewers (%)
<300	70	10
300-499	13	20
500-900	10	35
>900	7	35
Material		
Clay	75	14
Concrete	15	60
Brick	5	25
Other	5	1

1.2.3 Evolution in sewer systems modelling

There is a range of hydraulic software packages available for modelling sewer systems, e.g. InfoWorks® ICM, SOBEK®, SWMM® etc. Most of these hydraulic software are built upon the Saint Venant equations to model the gradual unsteady flow conditions of a sewer network. Saint Venant accounts for 1-Dimensional flow in channels with an open water surface. The first equation accounts for continuity of the flow (equation 1.2-2) and the second is the dynamic momentum equation (equation 1.2-3). Looking at the dynamic equation below, the first term is time dependant and applies to non-uniform, unsteady flow conditions, the second two terms include spatial variation only and therefore apply to the non-uniform steady conditions, the final two terms have no variation and hence account for the uniform, steady flow conditions (Butler and Davies, 2011).

$$B\frac{\delta y}{\delta t} + \frac{\delta Q}{\delta x} = 0 \quad (1.2\text{-}2)$$

$$\frac{\delta Q}{\delta t} + \frac{\delta}{\partial x}\left(\frac{Q^2}{A}\right) + gA\frac{\delta y}{\delta x} + gA(S_f - S_0) = 0 \quad (1.2\text{-}3)$$

Where,
Q = Volumetric flowrate (m^3 s)
g = Gravitational acceleration (m s^{-2})
A = Cross sectional area (m^2)
B = Water surface width (m)
S_0 = Bed slope (m/m)
S_f = Friction slope (m/m)
x, y = Longitudinal, vertical coordinate

The following assumptions have been made in the derivation of the St. Venant equations:

- The distribution of pressure within the fluid is hydrostatic
- The slope of the pipes considered is so shallow that the vertical flow depth is approximately equal to that if the pipe was lying flat
- The flow channel is a prism

- Velocity distribution is uniform across the pipe cross section
- Frictional losses calculated for steady flow are valid
- Lateral flow is neglected

1.2.3.1 Deterministic modelling

Models that have been developed to date have been largely focussed on gross solids movement in the sewers using deterministic modelling techniques. Butler et al. (2003) developed a deterministic model using Hydroworks® for the transport of gross solids in larger sewers (nappies, sanitary towels, faeces, tampons etc.). This was a velocity decrement model which calculates solid velocity relative to flow velocity (Butler et al, 2003a). An alternative modelling approach is the use of the Mach model, this deterministic model recognises that the presence of solids in the water modifies the surrounding water conditions, which in turn affects the transport of solids (Gormley and Campbell, 2006a; Gormley and Campbell, 2006b; Gormley et al., 2013). In 2006, Gormley and Campbell proposed a 'modified Mach model' to cope with the changing nature of transport mechanisms. This model is particularly appropriate when solids are close to deposition (movement in shallow pipes or when flow is very low and intermittent e.g. hydraulic jump, pooling behind solid, upstream of junction etc.) (Gormley & Campbell, 2006a; b). In 2013 this model was used to assess the appropriate design of a simplified sewerage network (on the urban fringes with shallow gradients) in order to reduce the risk of blockage and need for maintenance (Gormley et al, 2013).

Penn et al (2014) presented a sewer model to assess gross solid movement in sewers with various levels of greywater reuse (GWR) uptake. The SIMBA6 software (an extension to EPA SWMM) was used in order to model the hydrodynamics (flowrate, velocity, capacity and Froude number) of up- and down-stream sections of an Israeli sewer system (Penn et al, 2014). This simulation included the full dynamic solution of the St. Venant differential equations. These deterministic approaches, however, model domestic wastewater production as a continuous discharge based on averaged data, assuming an identical water use pattern for all residents. In reality, individual household wastewater profiles are a non-continuous series of discrete points. To model household discharges in a way that is more representative of this reality a stochastic model is needed.

1.2.3.2 Stochastic modelling

Stochastic sewer modelling is based on the idea that humans are predictable and there is a probabilistic element to how we use water in households. There have been few previous attempts to model stochastic sewer flow. Butler and Graham (1995) showed that the diurnal sewer inflow pattern can be described by a series of intermittent, rectangular impulses into the sewer system. In the model they developed, discharge impulses were introduced through a flow monitoring campaign.

Blokker et al. (2010) suggested a stochastic model for drinking water networks that was based on statistical data from surveys rather than flow measurements. This model was developed to avoid large measurement campaigns and bases its approach on the probability distribution functions relating to the end-uses of drinking water (i.e. intensity, duration and frequency of use, probability of use over the day). This drinking water model, named SIMDEUM®, was further developed by Elías-Maxil et al. (2014), who proposed a model that incorporates a delay and attenuation in order to better describe minor sewer input at dry weather flow. Pouzol et al. (2015) adapted this model to simulate excretion of drugs in urine as the appliance specific nature of the model allows specific quality discharges to be described.

Penn et al. (2017) suggested a model with reduced input requirements than those based in the work of Blokker et al. (2010), which was intended to help further assess gross solids movement in the upper reaches of sewer systems (following on from their previous works). This new stochastic wastewater generator does not require a great amount of input data but is instead based on empirical sampling. Therefore it assumes that the observed flow data (from 15 households) represents the flow of the target population. To model future changes in water use that have not yet been observed a model based on deterministic methods or empirical sampling will not be sufficient.

Pieterse-Quirijns et al. (2012) presented an adapted version of SIMDEUM®, named SIMDEUM WW® for use in drainage application. This additional module takes the drinking water model and adjusts the demand patterns to represent appliance-specific sewer discharge pulses. This also provides the possibility to link appliance-specific water quality parameters to the discharge pulses with the hope to quantify when and how much nutrient and thermal energy are discharged into the sewer network. This element of the model has not been used in a great number of application to date and has not yet been validated.

1.3 The future of urban sewerage systems

1.3.1 Trends and transitions in urban water management

Urban water management has evolved over history to meet the socio-political needs of the time. Brown et al. (2008) devised a framework outlining three phases of our transition towards water sensitive cities, see Figure 1.3-1. The first three stages of the transition framework give an explanation of how today's drainage networks have come to be. Our sewer systems were originally built to transport wastewater to the city limits to protect public health. As urbanisation continued, larger areas of land became unavailable for rainwater drainage; sewers were used to quickly transport stormwater out of the cities. The latter phases of the diagram propose where we are now and what we are working towards. Now adopting technology that works with the natural environment, boosting resilience and making the most of waste products that could be recovered and reused.

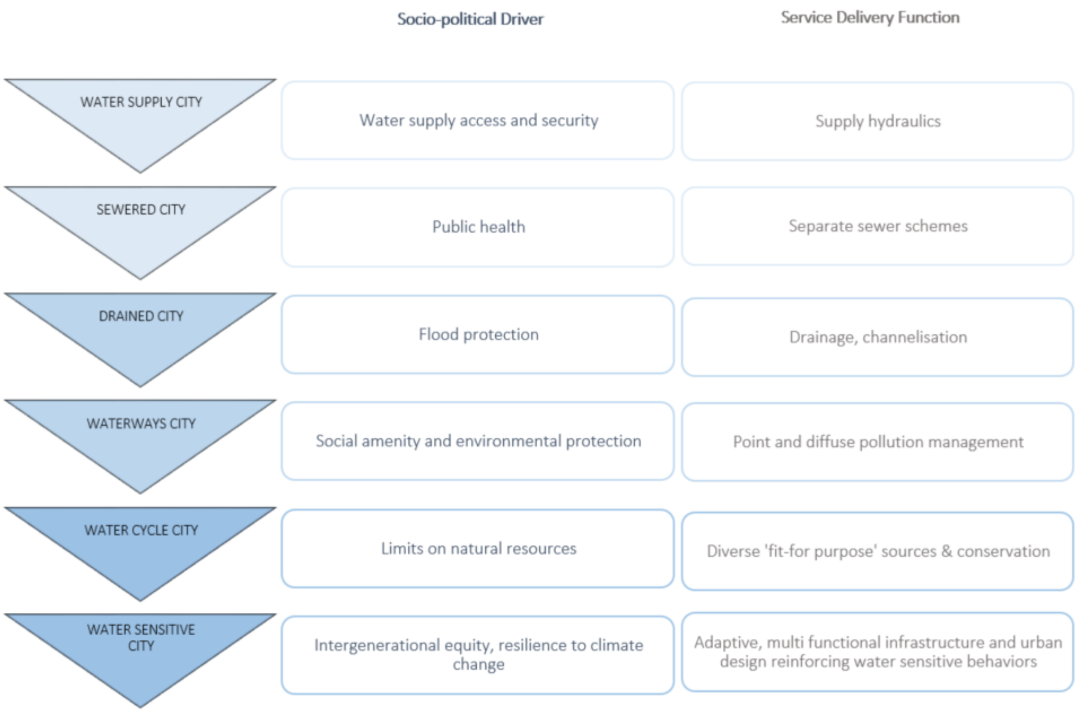

Figure 1.3-1. Transition Framework for urban water management (Brown et al., 2008)

The water sector is evolving to look for sustainable solutions for modern developments, focusing on alleviating water stress and reducing environmental impact. UKWIR (UK Water Industry Research Ltd.) is responsible for facilitating research that is relevant for the UK water industry. They have outlined a collection of 'big questions' that represent the key challenges for the UK water industry today (UKWIR, 2019). The key challenges for wastewater infrastructure are listed below.

UKWIR's ''Big Questions'':

- How do we halve freshwater abstractions in a sustainable way by 2050?
- How will we deliver an environmentally sustainable wastewater service that meets customer and regulator expectations by 2050?
- How do we achieve zero uncontrolled discharges from sewers by 2050?
- How do we remove more carbon than we emit by 2050?
- How do we maximise recovery of useful resources and achieve zero waste by 2050?

Conserving water sources, turning waste into opportunity and reducing harmful impacts to our environment are the common themes of importance. Furthermore, by halving water abstractions it is reasonable to assume that domestic water demand will need to reduce. Anglian Water are a UK water company that have the goal to reduce average water demand to 80 L $person^{-1}$ day^{-1}, this is almost half the current usage (Anglian Water, 2017).

By 2050, 50% of humans will live in areas of severe water stress (OECD, 2012). Climate changes are set to make rainfall patterns increasingly unstable, which means more droughts and more intense rainfall events. There is a pressing need to conserve and protect our water resources. This need gives rise to short cycled approaches to wastewater treatment, recovering and reusing whatever we can. Many countries are looking towards conservation and reuse strategies, including water use of quality fit for purpose (Bieker et al., 2010; Brown et al., 2010; Friedler et al., 2005; Wiener et al., 2016). The ZeroWasteWater is an example of a treatment plant concept that aims to make better use of water, energy and nutrients in the wastewater system whilst sufficiently reducing pathogens and pollutants (Verstraete and Vlaeminck, 2011). The diminishing water availability per head, shapes the urgent need for a cradle-to-cradle approach in future sustainable sewerage innovation.

1.3.2 Sustainable urban sewerage systems

Sustainable development and it's definition has been discussed and analysed at length (Lüthi et al., 2011; Parkinson, 1999) but ultimately , it offers the ability for humans to live their lives in sync with nature rather than against it. The circular economy is a concept for sustainable development that urges us to think of our processes as cyclic, every waste becomes a resource for another process (The Ellen MacArthur Foundation, 2015). Circular systems inherently require an integrated approach to process design. Integrated urban water management (IUWM) moves beyond being water sensitive and aims to transform urban living by offering optimum water efficiency whilst also providing recreational, environmental and cultural benefits (Hunt et al, 2005). Numerous projects around the globe are transforming the water cycle to enhance sustainability and wellbeing. Most of these IUWM pilot projects operate on a cluster (neighbourhood) scale. An example of an innovative wastewater collection and treatment system has been developed in Sneek, The Netherlands, where the wastewater from 232 households is collected in a concentrated form and used to recover nutrients and energy for the community. Domestic water use has dropped by 25-50% through utilising modern, water-saving appliances such as 1 L flush toilets (WaterSchoon, 2011). Anaerobically digesting concentrated sludge and kitchen waste produces around 12% of the communities gas demand. Heat is recovered from the greywater effluent and sludge digestion and the nutrients are recovered from the dewatered sludge through struvite precipitation (Hernández Leal et al, 2010; Verstraete & Vlaeminck, 2011).

IUWM examples like Sneek show great integration of water savings and resource recovery but there is still the question of how these examples would fit into our existing infrastructure. Most localised urban assessments outline that sustainable integrated water planning incorporates various levels of decentralised and centralised treatment systems as well as onsite operations (Brown et al, 2010). It has sometimes been presented as though smaller decentralised and large centralised treatment options are competing or exclusive but the benefits of integrating the two are increasingly being recognised (Bieker et al., 2010; Brown et al., 2010; Marlow et al., 2013; Van Afferden et al., 2015). This way we can address how sustainability can be integrated into our urban water cycles without a complete system overhaul, which wouldn't be a viable option.

1.3.3 Role of the sewer in enhancing resource recovery from the water cycle

Verstraete & Vlaeminck (2011) made a strong case for limiting dilution in the wastewater system to enhance the opportunity for recovery of energy and other resources. The more dilute wastewaters become the more difficult effective resource recovery becomes. Under average household consumption it could be possible for centralised treatment plants to receive wastewaters with a concentration around 750 mg COD L^{-1}. However, infiltration and stormwater dramatically reduce this to closer to 225 mg COD L^{-1} (Verstraete & Vlaeminck, 2011). Infiltration of groundwater into UK sewers can be as high as 15-50% of dry weather flows (Ellis and Revitt, 2002). Brombach et al. (2005) suggested that installing a separate sewer system could increase pollutant concentration by up to 85% and if infiltration was simultaneously halved, then this could rise to 140%. Furthermore, household water conservation of 25% could further concentrate wastewaters to 190% the present combined value (Verstraete & Vlaeminck, 2011). Returning to the Waterschoon project in Sneek (NL), blackwater from vacuum toilets and concentrated greywater are collected and energy is generated on site, i.e. dilution and infiltration is not a problem. The collected wastewater concentration amounts 11300 mg COD L^{-1} and enough energy is generated to power both the concentration of greywater and excess heat and power to feed back to the community (Hernández Leal et al., 2010). It is apparent that with a combination of sewer upgrades and water conservation a more concentrated wastewater could be achievable.

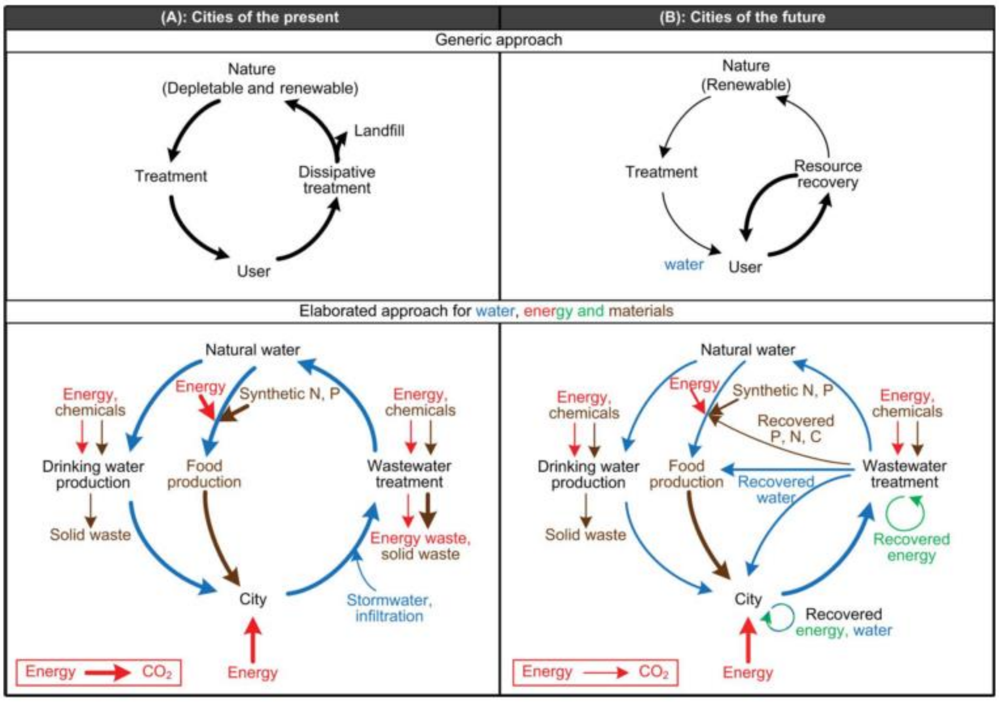

Figure 1.3-2. A vision for water, energy and material flows in the cities of the future (B) in comparison to the cities of the present (A) (Verstraete and Vlaeminck, 2011)

1.3.3.1 Boosting energy generation

Low organic concentration in sewage is the main barrier to energy generation. Tchobanoglous & Burton (1991) suggest 1500-2000 mg COD L^{-1} as a minimum to produce enough energy from biogas to heat the digester itself. Limiting sewer dilution is one option that could be used to increase energy generation but various research groups have been exploring other options of raising sewage concentration, such as introducing food waste to the sewer flow via kitchen grinders (Bolzonella et al., 2003; Legge et al., 2017; Verstraete and Vlaeminck, 2011). Legge et al. (2017) have been developing a model for the transport of food particles within the sewer to observe their impact on existing infrastructure. Bolzonella et al. (2003) investigated the impacts of kitchen grinders on nutrient recovery and sewer sedimentation/blockages. They revealed that in fact 78% of the foodstuffs failed to settle due to the lower specific gravity. They also found that nutrient removal was improved due to higher COD/N and COD/P ratios. Although this resulted in an increase in oxygen use and sludge volume during treatment, this was compensated with a threefold increase in biogas production.

1.3.3.2 More effective nutrient recovery

More concentrated wastewater also delivers more effective recovery of nutrients. Phosphorus recovery from sewage sludge could provide 15-20% of global phosphorus demand. Phosphorus can be recovered in various ways at various parts of the treatment process but all recovery options become more efficient at higher concentrations. Recovery efficiency can be dramatically improved from 31% to 85% through thickening (Cieślik & Konieczka, 2017). Penn et al (2013b) predicted that through various levels of water conservation alone could give an increase of 9-57% in NH_4^+-N and 8-52% in PO_4^{3-}-P.

1.4 Water conservation

For a collection of developed countries, water shortage and drought have been long standing problems. Conserving water is a paramount concern and many studies have aimed to assess the impact of various water saving strategies (Brown et al., 2010; Parkinson et al., 2005; Penn et al., 2012; Penn et al., 2014; Sun et al., 2015). There are multiple options to increase the availability of water, which include innovative appliances to reduce demand at source (e.g. low flush toilets, water-saving showers), or utilising an alternative water source that reduces the fresh water demand (e.g. rainwater harvesting (RWH), greywater reuse (GWR)).

1.4.1 Water saving appliances

Innovative devices have emerged to reduced water used by the consumer, e.g. low flush toilets, water saving showers, aerating taps etc. These appliances should reduce water demand but also be capable of equal functionality. Figure 1.4-1 presents the typical domestic water use in the UK. One third of water used in the home is used to flush the toilet and this has been a main target for demand reduction. Littlewood et al. (2007) compared the drainage capacity of an ultra-low flush toilet (Propelair®, 2017) with the standard UK toilet. The Propelair® uses low pressure air to assist the flush, using only 1.5 litres for cleaning, this has the potential to save 87% of toilet water (Millán et al., 2007). It was found that the ultra-low flush toilet outperformed the conventional toilet in flushing capacity but only when using a 50mm outlet pipe (Littlewood et al, 2007). The current building regulations call for a 75-100mm outlet pipe (depending on toilet design) (BS-EN-12056, 2000) but in spite of this the Propelair® toilet has a growing customer base in the UK. The European Commission published in their technical report that there is no evidence to suggest that low-flush toilets and urinals cause problems in the sewer but did highlight that further exploration of this was needed (Genty et al., 2013). A project has recently begun at the University of Exeter to assess the sewer effects of installing 120 Propelair® toilets across the university campus (Melville-Shreeve et al., 2019; University of Exeter, 2018). This study should provide needed insights into the downstream effects of these water-saving devices.

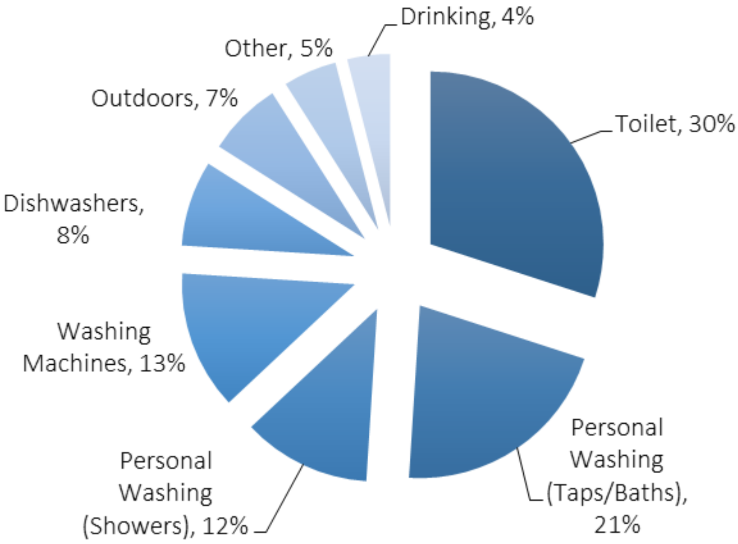

Figure 1.4-1. Breakdown of water usage within households in the UK, average per capita water consumption is approximately 140 L day^{-1} (WATERWISE, 2016)

1.4.2 Alternative water sources

Many household water uses do not require water to be of a potable standard. For example, we could flush the toilet or water the garden with water of a lesser quality, this would reduce the demand on fresh water sources without reducing the physical water used for that task. Parkinson et al. (2005) demonstrated the possibility to reduce water demand by 15-30% using stormwater and greywater for toilet flushing. A pilot project in Israel observed a GWR installation in a multi-storey building (Friedler et al., 2005). The system was able to treat greywater for on-site use (60-80% total) and it was highlighted that this technology could save 10-25% of urban water demand.

When planning the 2009 Melbourne sewerage strategy, water conservation was high on the agenda (Brown et al., 2010). Several conservation options were explored at different scales for their impact on water demand, cost, nutrient recovery and treatment capacity. The comparison included on-site, cluster or large central treatment with greywater reuse for toilet flushing and/or irrigation, urine separation and sewer mining. The favoured strategy purely for conservation purposes included onsite greywater reuse and sewer mining for irrigation both saving over 20% of the total water demand (Brown et al., 2010). This study highlighted the benefits of reuse in densely populated areas, i.e. apartment blocks, and the opportunity to utilise this in our increasingly urbanised world is becoming apparent. More recent research into alternative water sources has turned to the wider effects of these methods on water supply and drainage infrastructure (Ahilan et al., 2019; Murali et al., 2019; Penn et al., 2013b; Sun et al., 2015)

1.4.3 Impact of water conservation on the sewer flow

1.4.3.1 Sedimentation

Reducing domestic water use has a direct effect on sewer systems by simultaneously reducing wastewater volume (Davis and Bursztynsky, 1980; Putty et al., 1992). A huge amount of water is currently required in order to keep our sewers clean by maintaining a flow velocity that prevents solids from settling (Libralato et al., 2012). A main challenge of reducing water use is sustaining this self-cleaning velocity within the sewer pipe. In order to reduce the flowrate whilst upholding the velocity, a smaller pipe diameter or greater incline is necessary. Smaller pipes are cheaper than larger ones but greater inclines mean costlier excavation. In the Californian drought of 1975-1977 it was suggested that, without adaption of the sewer, water conservation of above 20% could cause sedimentation and consequently problems with hydrogen sulphide production, furthermore, the necessary pipe incline to maintain minimum flow velocity would become very steep (for 75% flow reduction the pipe slope would need to double) (DeZellar and Maier, 1980).

Penn et al. (2013b) confirmed that flow, velocity and proportional depth reduced with increased greywater reuse in Israel (10-40% discharge reduction). However, the model indicated that minimum velocities were by the most part still achieved and therefore would not be likely to increase sewer blockages.

1.4.3.2 Increased capacity

Penn et al. (2012) assessed the potential use of GWR to soften the effects of peak usage. Water use in cities tends to follow a diurnal pattern with peaks in the morning and evening. In this analysis, there were three scenarios, the first presented a no GWR case, the second utilised GWR for toilet flushing and the third employed GWR for toilet flushing and irrigation. During the morning peak wastewater flows were reduced by 13-53% and 43-58% as a result of scenarios two and three respectively (Penn et al., 2012). As sewers are designed with account of peak flow, this softening could greatly increase capacity, thus alleviating effects of urbanisation.

Penn et al. (2013b) moved on from this to focus on changes to infrastructure that could be enabled by GWR. They found that, at high rates of GWR (for toilet flushing and irrigation), there was opportunity to move down a pipe size class, which could save money whilst maintaining flowrate. Although the chance to move down a size class was not reported in all GWR cases, this does highlight the potential to increase sewer connections or postpone sewer enlargements. The maximum proportional depth used in this assessment was too low (for purposes of comparison), meaning pipes were required to run emptier than is possible. As a consequence, it is thought that pipe size decrease would be possible in more cases than stated in this study. Decreasing pipe diameters is of economic interest but it should be noted that in a combined sewer system there may not be a substantial effect as capacity must be reserved for stormflow.

1.4.4 Modelling changes to sewer flow

There has been a growing body of work from a research group in Israel, aiming to assess effects of future water use changes on the sewer system (Penn et al., 2013a; Penn et al., 2012; Penn et al., 2013b; Penn et al., 2014; Penn et al., 2017). These works have been focussed on greywater reuse and considered three household types for this analysis, 1.) no GWR implemented, 2.) GWR utilised for toilet flushing and 3.) GWR used for toilet flushing and irrigation. Five scenarios considered various levels of penetration achieved over time. After 20 years, still 70% of the population were predicted to have made no change. These future projections seem somewhat under-ambitious when considering some other projections (Agudelo and Blokker, 2014; Artesia, 2018; Poortvliet et al., 2018). Penn et al. (2012) presented a first step towards quantifying the effects of GWR on wastewater quantity and quality, predicting a 26-42% reduction in wastewater quantity and 30-60% rise in wastewater concentration (on individual household basis). This work then moved on to consider how infrastructure could change or uptake could be managed to optimise the implementation of GWR. Penn et al. (2013a) performed a multi-objective genetic optimisation to find the minimum wastewater discharge and minimum cost of GWR systems when ensuring minimum flow velocity (for solids movement) was maintained. Whilst Penn et al. (2013b) aimed to address how pipe diameters could change to allow adequate sewer transport under GWR. Penn et al. (2014) presented a sewer model to assess gross solid movement in sewers with various levels of GWR uptake, described in Section 1.2.3.1. This study considered the upper and lower sewer reaches separately. In the upper reaches of the sewer, flow is intermittent and therefore large, unsubmerged solids are more common. Whereas in the lower reaches the flow is continuous and the solids are likely to be smaller and submerged. This study concluded that the downstream movement remained relatively unchanged when GWR was implemented, however, blockage was much more likely in upper reaches (solids remained stationary for 76% of the day) (Penn et al., 2014).

1.4.5 Impact of water conservation on wastewater quality/composition

1.4.5.1 Wastewater treatment efficiency

Enhanced treatment efficiency due to more concentrated wastewater during drought has been experienced many times in history. Healthier receiving waters were a result of this more efficient treatment coupled with the decreased volume of effluent discharged (DeZellar and Maier, 1980). An average flow reduction of 24% was experienced by several WWTPs across California during the 1975-1977 drought (Davis and Bursztynsky, 1980; DeZellar and Maier, 1980). The influent BOD concentration was observed to rise by 25-40%, this resulted in approximately 10% decrease of BOD effluent for a 40% flow reduction (DeZellar and Maier, 1980). Davis and Bursztynsky (1980) confirmed that treatment efficiency improved during flow reduction, mainly due to the increased solids removal in clarifiers. More concentrated wastewaters experience better settling (Verstraete and Vlaeminck, 2011). A 10-20% flow reduction extended the time until design capacity of process units was reached, with the exception of the biological treatment. It was suggested that the performance of biological treatment should be enhanced to allow intensification of the entire process (Davis and Bursztynsky, 1980). Since this study was conducted, novel innovations have enabled the potential for great intensification and flexibility of biological treatment systems (e.g. Nerada technology (Royal Haskoning DHV, 2017)).

1.4.5.2 Resource recovery

Increased wastewater concentration has been discussed to be beneficial for resource recovery (energy and nutrients) (Bolzonella et al., 2003; Brombach et al., 2005; Penn et al., 2013b; Verstraete and Vlaeminck, 2011; Warith et al., 1998). This has been discussed in Section 1.3.3.

1.4.5.3 Surface water

If more concentrated wastewater is conveyed within a combined sewer network, the risk of CSO's causing damage to the environment will increase due to the higher pollutant loading. In a combined sewer, at times of heavy rain, a pulse flow travels through the sewer dislodging any sediments that have built up over the dry period. This potent flow is transported to the treatment plant or indeed released to the environment via a CSO. Rainfall events often cause an initial spike in concentration arriving at the WWTP, as time progresses the influent becomes very dilute and large in volume. Parkinson et al. (2005) took an overview of various levels of domestic water conservation and reuse strategies in order to assess the effects on water consumption, dry weather flow (DWF) velocities, CSO potency and treatment efficiency. Each strategy was compared to the then standard case of a 9 litre flush toilet (now 4/6L). Although, wastewater treatment efficiency was found to improve under a slightly reduced DWF velocity (up to 11%) and CSO potency was shown to increase due to increased sedimentation and concentration of pollutants, with the exception of stormwater reuse (Parkinson et al., 2005; Parkinson, 1999). The principle objectives of this study were to lower water demand and reduce pollutant loads in CSO's therefore particular favour was expressed for rainwater harvesting as a water conservation method.

1.4.5.4 Odour and corrosion

As previously mentioned, water conservation practices have raised concerns due to an increased risk of sedimentation, which could lead to blockages, odours and corrosion (Marleni et al., 2011; Marleni et al., 2015; Marlow et al., 2013; Sun et al., 2015). Studies carried out in Australia investigated the increased production of problematic odours, CH_4 and H_2S under reduced water use (Marleni et al., 2011; Marleni et al., 2015; Sun et al., 2015). Marleni et al. (2015) investigated the increase in wastewater parameters that influence the formation of hydrogen sulphide and found that water saving scenarios did increase the concentration of these parameters by up to 50%. Rainwater harvesting was found to have the lowest increase in concentration overall but a much higher concentration of iron (due to galvanised iron roofing in the study catchment) than the other scenarios. This high iron content is beneficial for odour and corrosion as it inhibits the formation of hydrogen sulphide.

1.4.5.5 Rheological properties

Raising the solids concentration is an additional effect of reducing water demand. Only 0.1% of the current UK wastewater is solid matter and this usually takes the form of larger objects within the flow, and is therefore unlikely to dramatically affect the rheology (DEFRA, 2002; Tchobanoglous and Burton, 1991). However, it is known that at lower sewer reaches solids become smaller and wastewater becomes a more homogenous mixture (Penn et al., 2014). It is reasonable to assume that large changes in wastewater concentration via source control could alter the rheological properties of wastewater through the system. There were a limited collection of studies available assessing the rheology of wastewater (Cheng and Li, 2015; Manoliadis, 1991; Ségalen et al., 2015) but in recent years a group in TU Delft has begun studying the impacts of concentrated domestic slurries emerging from vacuum toilets and food waste disposers (Thota Radhakrishnan, 2019). Sewage sludge exhibits complex properties that involve the coupling of pseudo-plastic (shear thinning) and power law models (2-15 TSS%) with exponential thixotropic (time dependent thinning) model (7-15 TSS%) (Cheng and Li, 2015). These models attempt to describe the properties of fluids that have a viscosity dependant on external conditions it is exposed to, i.e. viscosity dependant on shear stress or duration of force applied. Thota Radhakrishnan (2019) suggested that significant changes to sewage rheology occur above 2% TSS which implies that sewage rheology should be considered when modelling in some new sanitation scenarios e.g. black water separation or installation of food waste grinders. Although rheological properties are not likely to be governing in a conventional sewerage system with its wide range of discharge concentrations.

1.4.6 Modelling changes in wastewater quality

A small number of studies have been conducted to assess the impacts of future water use on wastewater quality. The studies that do exist, consider specific selection of appliances such as low flush toilets, GWR (Parkinson et al., 2005; Penn et al., 2013b) or RWH (Parkinson et al., 2005). Parkinson et al. (2005) utilised the Hydroworks software to predict water consumption, CSO potency and treatment efficiency under various water conservation measures. A deterministic input profile for domestic wastewater generation was used (Parkinson, 1999). The effect of treatment efficiency was explored under dry weather flow conditions using the ASM1 model, rainwater was neglected as it knocks out treatment benefits. Of the scenarios investigated reducing toilet flush volume boosted household concentration by 10-24% and greywater reuse increased by 42%. Average wastewater discharge concentration was considered which does not reflect that certain discharges will hold most of the pollutant concentration (e.g. toilet flushes). Penn et al. (2013b) reported pollutant concentration increases of 6-42% COD, 7-73% TSS, 9-57% NH_4-N and 7-52% PO_4-P for flow decreases of 8-41%, achieved through various levels of GWR. This work showed the shallowing of wastewater concentration through a sewer system, modelled using SIMBA6 (Ifak, 2009). The same wastewater quality profile was used for each household adopting the same level of GWR, developed in Penn et al. (2012). As previously mentioned a stochastic input model for this model was developed in Penn et al. (2017) but there was no linkage made between input flows and there appliance-specific water quality. Both the water quality models mentioned (Parkinson et al., 2005; Penn et al., 2013b) are deterministic models considering domestic sewer input as a continuous parameter for the current population. They assume an average population and usage pattern that is representative of the measured data. It is worth noting that these models do not consider the transformation of sewage in transit, considering wastewater quality as a consequence of discharge concentration, dilution and sedimentation within the system.

1.4.6.1 Household wastewater quality

Future scenario sewer models produced to-date have assumed deterministic hydrographs (representation of the discharge rate over time) and pollutographs (representation of a pollutant concentration over time) rather than specifically linking discharges to their appliances. This could be improved by including the differing concentrations produced by appliances and would lead to more flexibility in scenarios that could be modelled. SIMDEUM® (Watershare, 2016), discussed in section 1.2.3.2, is a tool that generates appliance-specific flow patterns based on probability parameters linked to appliance usage, household composition, and consumer water use behaviour (Blokker et al., 2010). Patterns produced by SIMDEUM® are specific to each appliance (e.g. toilet, sink, washing machine, etc.) which makes it possible to investigate explicit water use changes without assuming typical water usage patterns based on historical data. SIMDEUM WW® extends from SIMDEUM® to convert demand patterns into wastewater discharges, including thermal and nutrient loads (Pieterse-Quirijns et al., 2012). This conversion is achieved through correcting the flow rate or delaying the time of discharge e.g. toilets can take minutes to fill but seconds to discharge. Thermal and nutrient loads from each appliance are incorporated into the discharge profile by assigning typical (per use) load to each appliance. SIMDEUM WW® originally included very little detail on pollutant discharges, having been used simply to demonstrate possibility for nutrient discharge modelling (Blokker and Agudelo-Vera, 2015; Pieterse-Quirijns et al., 2012). There have been a number of studies to describe wastewater quality produced from household appliances that could be used to improve SIMDEUM WW® (Blokker and Agudelo-Vera, 2015; Butler et al., 1995; Parkinson et al., 2005; Parkinson, 1999; Siegrist et al., 1976; Surendran, 1998). A review of the relevant literature showed that there was a wide variation in average concentration which raises questions of the reliability of the data. The review also revealed that a significant amount of time has passed since these studies were conducted and since then water-user habits and appliances have changed. Even the most recent studies of Blokker and Agudelo-Vera, 2015 and Parkinson et al., 2005 utilise wastewater quality data from the earlier work from as early as 1970's. This shows a clear need for new studies of this nature to better inform models such as SIMDEUM WW®. Wastewater quality was often reported in concentration form which is specific to the discharge volume of the appliance being monitored. Table 1.4-1 shows the wastewater quality found in various literature sources in the form of mass input to the sewer system rather than a concentration form.

Table 1.4-1. Water use and sewage quality associated with household appliances (adapted from Parkinson (1999) and Blokker and Agudelo-Vera (2015))

Appliance	*Water use (L use⁻¹)*	*Sewage quality (g use⁻¹)*						*Reference*
		BOD	COD	SS	TKN	NH_3	P	
Bath	74	14.21	20.87	-	-	0.10	-	(Laak, 1974)
		12.58	-	8.88	1.26	0.15	0.15	(Siegrist et al., 1976)
		15.98	31.38	5.62	-	0.12	-	(Surendran, 1998)
		18.50	-	-	-	0.11	-	(Butler et al., 1995)
		14.06	25.90	8.88	0.444	0.12	0.15	(Parkinson et al., 2005; Parkinson, 1999)
		15.98	31.38	-	0.56	-	0.03	(Blokker and Agudelo-Vera, 2015)
Shower	36	-	-	-	-	-	-	(Laak, 1974)
		6.12	-	4.32	0.61	0.07	0.07	(Siegrist et al., 1976)
		7.78	15.26	2.74	-	0.06	-	(Surendran, 1998)
		9.00	-	-	-	0.05	-	(Butler et al., 1995)
		6.84	12.60	4.32	0.36	0.06	0.07	(Parkinson et al., 2005; Parkinson, 1999)
		7.78	15.26	-	0.27	-	0.07	(Blokker and Agudelo-Vera, 2015)
Wash basin	3.7	0.87	1.42	-	-	0.004	0.18	(Laak, 1974)
		-	-	-	-	-	-	(Siegrist et al., 1976)
		0.93	1.60	0.15	-	0.002	-	(Surendran, 1998)
		0.55	-	-	-	0.0006	-	(Butler et al., 1995)
		0.87	1.48	0.555	0.04	0.002	0.10	(Parkinson et al., 2005; Parkinson, 1999)
		0.51	1.60	-	0.03	-	0.05	(Blokker and Agudelo-Vera, 2015)
Kitchen sink	6.5	4.39	8.97	-	-	0.04	0.085	(Laak, 1974)
		5.20	-	4.68	0.44	0.04	0.48	(Siegrist et al., 1976)
		3.48	6.08	-	-	0.03	-	(Surendran, 1998)
		4.91	-	-	-	0.03	-	(Butler et al., 1995)
		4.42	7.48	4.68	0.26	0.03	0.26	(Parkinson et al., 2005; Parkinson, 1999)
		1.16	6.08	-	0.48	-	0.06	(Blokker and Agudelo-Vera, 2015)
Dishwasher	30	-	-	-	-	-	-	(Laak, 1974)
		19.50	-	13.20	1.20	0.14	2.04	(Siegrist et al., 1976)
		3.30	-	2.70	-	-	-	(Surendran, 1998)
		-	-	-	-	-	-	(Butler et al., 1995)
		31.20	30.00	13.20	1.50	1.50	2.04	(Parkinson et al., 2005; Parkinson, 1999)
		12.42	80.25	-	1.20	-	2.04	(Blokker and Agudelo-Vera, 2015)
Washing machine	90	25.38	65.25	-	-	-	15.39	(Laak, 1974)
		16.20	-	17.10	1.17	1.17	3.60	(Siegrist et al., 1976)
		9.90	-	8.10	-	-	-	(Surendran, 1998)
		59.58	-	-	-	-	-	(Butler et al., 1995)
		25.20	65.25	17.10	1.80	1.80	2.88	(Parkinson et al., 2005; Parkinson, 1999)
		15.21	65.25	-	0.68	-	1.26	(Blokker and Agudelo-Vera, 2015)

1.5 Future projections for water use

The future of water use is uncertain and can be influenced by a multitude of factors - whether social, economic, political, technological, environmental or demographic. The realisation of these future impacts on variability of water use has led to increased interest in developing forecasting and plans for future water management (DEFRA, 2016). UK water companies are required to submit Water Resource Management Plans to the regulator that project 25 years into the future. These plans consider factors such as population growth, climate change and the ability to transfer water between locations. Amounting from this need to look ahead at future use, there have been several studies aiming to simulate the effects of future uncertainties on water availability and domestic use (Alcamo et al., 2007; Hargreaves et al., 2019; Makropoulos et al., 2008; Parker and Wilby, 2012).

Alcamo et al. (2007) used a global resource model to analyse the impacts of socio-economic issues and climate change on global water use. They utilised predictions of The Intergovernmental Panel on Climate Change (IPCC) to predict effects of income, electricity production, water-use efficiency and other driving forces, on water stress. This study revealed that income had a much larger effect on water use than population growth and that socio-economic factors had greater influence than climate change. This, therefore, suggests that largest impact on water use are factors within our control. Hargreaves et al. (2019) recognised that future water use choices are dependent on aspects of spatial planning. Factors such as population density, dwelling compaction and variability in roof areas are likely to impact future feasibility of water-saving options. This study found that RWH uptake was greatly affected by spatial planning whereas the feasibility of household-GWR would be more depend on the system cost and its water-savings. This integrated modelling framework, tested in the South East of England, suggests that local studies could be used together with residential densities, rainfall and water price to better inform future water-saving potential of a specific area. In this way, planning authorities could work closely with water companies to deliver future water savings.

Sewer systems are often built to last decades or even centuries and the question arises of how robust these systems are to deal with changes such as rapid urbanisation, water stress or technological advancements e.g. 1 litre flush toilets. Agudelo and Blokker (2014) addressed the robustness of the drinking water distribution system (DWDS) in three case study areas in the Netherlands. They used SIMDEUM® and EPANET® to simulate ten future water use scenarios for their effect on the drinking water distribution system. These scenarios ranged from dramatic demand reduction, e.g. 100% adoption of 1L flush toilets, to and increased demand through the 100% adoption of luxurious shower heads. This study found that for most scenarios the DWDS was robust enough but for dual source scenarios (toilet, laundry and outside tap not served by DWDS) the water age increased by up to 54% which could have negative effects on water quality but more research is needed to define these limits.

Artesia Consulting produced a report on behalf of OFWAT to explore the possibility of delivering large reductions in water demand in the UK (Artesia, 2018). This report highlighted some future projections for water use in the UK based on social, political and technical outcomes (see Figure 1.5-1). The outcomes where generated through consideration of historic trends and surveys for consumers and water industry professionals. Potential cost and implications of these scenarios was outside the scope of this work but it was recommended that this be addressed with future studies.

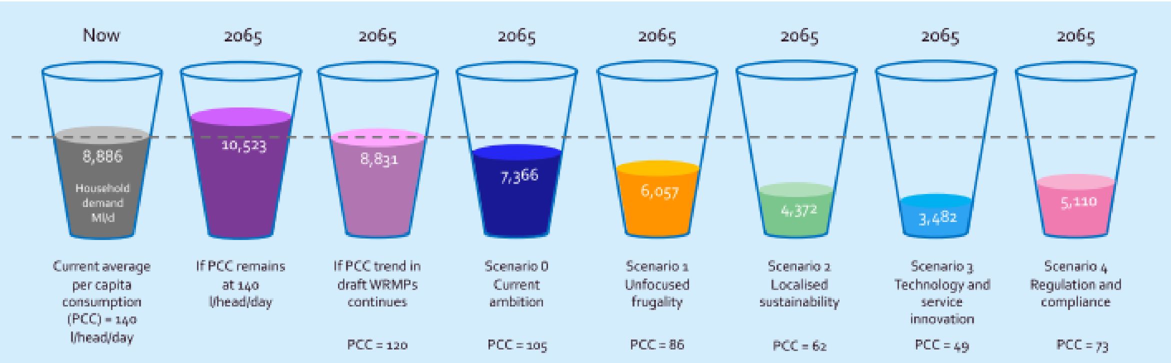

Figure 1.5-1. Future water use scenarios for the UK developed by Artesia (2018) on behalf of OFWAT

1.6 Concluding remarks

Wastewater is a nutrient and carbon-rich, abundant, and increasing resource that presents ample opportunities for recovery of nutrients and energy. It is not currently utilised to its full potential and one reason for this is the level of dilution in the sewer network. There are calls for a paradigm shift in urban wastewater systems to boost sustainability and environmental sensitivity. The need to conserve water into the future could be important for improving treatment efficiency, capacity and recovery of resources.

There is a growing body of work that attempts to better understand the effects of future water use and addressing the robustness of our current infrastructure. A variety of sewer models have been developed for various purposes, these models have been largely deterministic or based on monitored data. There is potential to develop these models further to include probabilistic, non-continuous domestic discharges, thus representing the true dynamics of a sewer system that will be necessary for quantifying the effects of future scenarios.

1.7 Aims and objectives

Household water conservation is an increasingly important topic and the appearance of water-saving devices is growing. This is coupled with a trend towards creating sustainable urban water systems. The literature has revealed a need to better understand the effect that future water use scenarios have on sewerage infrastructure. There has been a small selection of sewer models developed for this purpose but these have been largely deterministic and dependant on the assumption that the measured data is representative of the modelled case. There has been less research to date into producing a network model based on purely probabilistic data.

It appears that there is space to develop stochastic modelling in the sewer to better represent the dynamics and diverse discharge patterns that are present in sewer systems. The model SIMDEUM® that was developed for the drinking water network and the extension, SIMDEUM WW®, offers a possibility to be used to represent sewer discharges on an appliance-specific basis, allowing a link to be made between water quality and appliance discharge. Thus, producing intermittent pulses into the sewer that represent a dynamic and non-continuous domestic discharge pattern. The SIMDEUM WW® extension needs further development with regards to appliance-specific wastewater quality and is yet to be validated.

The overarching aim of this thesis is, therefore, to develop a stochastic sewer model that can be used to observe and simulate the changes to wastewater flow and quality that could arise from future water use. This is with a view to improve sustainability within the urban water cycle.

To achieve the above aim, the core objectives of the project were defined as follows:

1. Integrate stochastic wastewater discharge patterns (using SIMDEUM®) into a sewer network model (based in InfoWorks® ICM) to produce a sewer model that includes unique household discharges that are linked to specific appliances.
2. Define wastewater quality profiles for typical household water-using appliances and use SIMDEUM WW® to generate appliance-specific wastewater discharge profiles. This wastewater discharge information will be included as an input to the InfoWorks® ICM water quality model to predict time-varying wastewater quality through the sewer.
3. Calibrate and validate the hydraulic and wastewater quality models using data collection from case study networks.
4. Test future water use scenarios using the sewer model to predict changes to flow and wastewater quality, with a view to indicate changes to sewerage condition e.g. solids transport, wastewater concentration, hydraulic and organic loading on the system.
5. Reflect on modelling outcomes to provide recommendations and implications of water conservation on sewer network design.

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Chapter 2

Developing a stochastic sewer model to support sewer design under water conservation measures

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2.1 Context

Following the review of sewer modelling literature in the previous chapter, it was found that stochastic models for addressing changes in water use are in their infancy and are not widely used within the UK water sector. Through collaboration with a local water company, Wessex Water, an InfoWorks® ICM model was obtained of a separated sewer system in one of their catchments. This model utilised deterministic modelling of household discharges based on downstream measurements. Every discharge pattern was identical and to attempt to address changes in water use with this approach would involve applying a reduction factor to the entire profile which would not be accurate. Some water-using appliances have more capacity to reduce their consumption than others and thus all appliances will be effected in a different way. It was decided to improve this modelling approach by using a stochastic input which would allow the user to predict impact of changes to population, user habits and household appliance specifications. SIMDEUM® was a software discovered through review of literature, which had the capability to generate unique demand patterns at small spatial and temporal scales. This software had been developed for Dutch drinking water application but there had been some development of a wastewater conversion module. However, it was not currently possible to use SIMDEUM® in conjunction with InfoWorks® ICM. Therefore, the aim of the following paper was to integrate stochastic wastewater discharge patterns (using SIMDEUM®) into a sewer network model (based in InfoWorks® ICM) to produce a sewer model that includes unique household discharges that are linked to specific appliances.

This chapter is submitted in an alternative format in line with Appendix 6A of the "Specifications for Higher Degree Theses and Portfolios" as required by the University of Bath.

The work completed in this paper was conducted by the author with the exception of the following:

- Continuous wastewater discharge profiles and network specifications were provided by Wessex Water.
- The monitoring campaign to obtain validation data was carried out by RPS (www.rpsgroup.com/water) contracted by Wessex Water in 2015.

Statement of Authorship

This declaration concerns the article entitled:	
Developing a stochastic sewer model to support sewer design under water conservation measures	
Publication status (tick one)	
Draft manuscript ☐ **Submitted** ☐ **In review** ☐ **Accepted** ☐ **Published** ☒ x	
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Candidate's contribution to the paper (provide details, and also indicate as a percentage)	The candidate contributed to / considerably contributed to / predominantly executed the… **Formulation of ideas:** Fully executed by candidate Supervision provided by Jan Hofman and Tom Arnot. **Design of methodology:** Fully executed by candidate Supervision provided by Jan Hofman and Tom Arnot. **Experimental work:** Fully executed by candidate with the exception of the following: - Continuous wastewater discharge profiles and network specifications were provided by Wessex Water. - The monitoring campaign to obtain validation data was carried out by RPS (www.rpsgroup.com/water) contracted by Wessex Water in 2015. Supervision provided by Jan Hofman and Tom Arnot. Software guidance provided by Mirjam Blokker. **Presentation of data in journal format:** Fully executed by candidate. Review and editing provided by Jan Hofman, Tom Arnot, Mirjam Blokker, Zoran Kapelan and Jan Vreeburg.
Statement from Candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.
Signed	 **Date** 16/07/2020

2.2 Journal of Hydrology paper

Developing a stochastic sewer model to support sewer design under water conservation measures

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2.2.1 Abstract

Population growth and climate change place a strain on water resources; hence, there are growing initiatives to reduce household water use. UKWIR (2016) have a stated aim to halve water abstraction by 2050. This will significantly reduce inflow to sewer systems and increase wastewater concentration. This work presents a new stochastic sewer model that can be used to predict both hydraulic and pollutant loading for various water saving scenarios. The stochastic sewer model is based on integration of the stochastic water demand model SIMDEUM® with the InfoWorks® ICM (Sewer Edition) hydraulic model and software. This model has been developed using foul sewer networks, i.e. where household discharges are the dominant inflow; however, it could also be used in combined sewage systems where rainwater flows would add to the stochastic dry weather flow (DWF). The stochastic sewer model was tested and validated on several real catchments in the Wessex Water area of the UK. Calibration was carried out using metered consumption data. The stochastic sewer model gives an accurate prediction of the diurnal patterns of sewage discharge at a household level and was validated using real flow measurements within the catchment. The results obtained indicate that this model can be used to accurately predict changes in flow due to water conservation. A preliminary study for the impact of low water use on this validated network model has been conducted and it was found that overnight and daytime flow was reduced by up to 80% whereas evening flows remained largely similar. Extended stagnation times were observed in the street scale pipes (150 mm) in the low water use scenario.

2.2.2 Keywords

Sewer design; Water conservation; Stochastic sewer modelling; Wastewater quality; Household discharge; Reduced water consumption

2.2.3 Introduction

Rising water scarcity, pressure for increased sustainability and the need for improved water efficiency will drive reduction in future water consumption and thus reduce the flow into sewers. For example, Anglian Water (2017) is aiming for less than 80 L capita^{-1} d^{-1} potable water consumption, and UK Water Industry Research (UKWIR) (2016) wishes to halve abstraction by 2050. What will be the effect on sewer systems and the way we dispose of wastewater? Sewers are traditionally designed for transporting wastewater and storm water from hard surfaces in urban areas to recipients such as wastewater treatment works, rivers or the sea. Sewer mains in the UK are sized based on rainfall events and an acceptable flooding return period of 20 years (BS EN 752:2008) (Butler and Davies, 2011). Similar approaches are used in other countries. In the case that the designed drainage capacity is exceeded, additional flood protection is achieved through combined sewer overflows (CSOs), where the surplus water is temporarily discharged untreated into surface water. This is of course a threat to the ecological health of the surface water body and therefore CSO frequencies should be minimised. For sustainability reasons, modern sewer design is moving towards separated sewers for foul and storm water, but also toward Sustainable Drainage Systems (SuDS), where rainwater is collected, stored and infiltrated in ponds and swales (Brown et al., 2008; Marlow et al., 2013). For the foul sewer system, the flow transported is therefore much reduced and only dependant on the water consumption of the connected users. Further reduction in water consumption will occur due to water saving programmes, and hence sewage concentrations will increase.

A new sewer design aimed at transporting more concentrated wastewater could increase efficiency and sustainability of wastewater networks. Increasing concentration of wastewater could lead to more effective sewage treatment and resource recovery (nutrients/energy), as well as reducing pollution to receiving waters (Verstraete and Vlaeminck, 2011). It has been suggested that sewer transport efficiency may be affected by reduced flow velocities and production of harmful gases (Parkinson et al., 2005; Penn et al., 2013; Sun et al., 2015).

It is therefore very important to predict and understand how developments in water use and drainage practice will affect the diurnal patterns of sewage flows and concentrations. The work presented here outlines the development and calibration of a stochastic sewer model for accurate prediction of dynamic sewage flow, pollutant content, and sedimentation changes, resulting from widespread water conservation. The model enables the study of future water use scenarios for their effect on the sewerage system. The consequences of future development, demographic changes, water technology developments and legislation changes can all be investigated. Many methods for increasing sustainability in the water cycle are becoming available, such as wastewater-reuse, rainwater harvesting and the recovery of heat or resources from wastewater. The methodology and model presented here will allow investigation of the impact of these technologies on the performance of sewer systems, and highlight the necessary design modifications to best support current sewer systems under substantially reduced future water use. The overall aim is to re-think sewerage systems to better serve communities through water conservation, resource recovery, and by providing a cleaner environment.

Previous sewer modelling efforts have been largely deterministic and typically explore the fate of large gross solids within the system (Butler et al., 2003; Gormley and Campbell, 2006). Penn et al. (2014) presented a sewer model to assess gross solid movement in sewers with various levels of greywater recycling (GWR). Within this study, SIMBA6 software was used to model the hydrodynamics (flowrate, velocity, capacity and Froude number) of up and down stream sections of an Israeli sewer system. When testing the effects of GWR on this network, the time that solids movement was achieved reduced from 67% to 24% of the day in the upper reaches. No such detrimental effects were identified for the lower reaches. There have been few previous attempts to model stochastic sewer flow. Elías-Maxil et al. (2014) proposed a model that incorporates a delay to a previously developed drinking water model (Blokker et al., 2010), in order to better describe minor sewer input at dry weather flow. Pouzol et al. (2015) adapted this model for use on a semi-rural network in order to simulate excretion of drugs in urine. Penn et al. (2017) suggested a model with reduced input requirements, in comparison to the aforementioned models, which is intended to help further assess gross solids movement in the upper reaches of sewer systems.

SIMDEUM® (Watershare, 2016) was developed as a methodology and tool to simulate drinking water demand in supply networks and calibrated for water use in the Netherlands. It generates stochastic water use profiles by utilising input parameters that have a physical meaning linked to appliance usage (typical flow), household composition (gender, age, occupancy) and consumer water use behaviour (number of toilet flushes, shower duration, time preference for appliance use etc.) (Blokker et al., 2010). SIMDEUM® differs from other tools of this nature by providing profiles with small temporal (1 s) and spatial (customer tap) scales.

The initial application of SIMDEUM® was to aid the design of self-cleaning water supply networks but it has since been developed to enable use in several other applications (Blokker et al., 2017). SIMDEUM WW® is one such development that describes wastewater discharge, including thermal and nutrient loads (Pieterse-Quirijns et al., 2012). Average nutrient concentration and water temperature produced by each appliance are linked to stochastic demand profiles (produced in SIMDEUM®) to produce a stochastic wastewater discharge profile. There are also some flow adaptations within SIMDEUM WW® which convert a demand profile into a discharge profile. The wastewater discharge profile is somewhat different from the water demand profile. Some appliances discharge quicker than they fill (e.g. toilets, baths) or discharge with a different profile than they demand (e.g. washing machines, dishwashers). External water use is also excluded from the wastewater profile. Whilst water supply flow patterns (SIMDEUM®) have been validated using measurements in the Netherlands and the USA there has been no such validation for wastewater patterns (SIMDEUM WW®).

The work presented in this paper describes the development of a stochastic sewer model based on SIMDEUM WW® household discharge patterns, as input to a hydraulic and water quality sewer network model in InfoWorks® ICM. The model is tested and validated for a case study provided by Wessex Water, a UK-based water utility company.

The paper is organised as follows; the methodology behind software calibrations and output validation is outlined in Section 2.2.4. The case study simulated using the model is described in Section 2.2.5. The output from the stochastic sewer model is presented and analysed in Section 2.2.6, this includes a preliminary study of future effects of water conservation on the sewer system. This is followed by the key conclusions to be made from this work in Section 2.2.7.

2.2.4 Methodology

InfoWorks® ICM (Sewer Edition; Innovyze Ltd, Oxfordshire) was used to simulate a residential, separated sewer network (i.e. excludes storm water) within the Wessex Water region of the UK (details of the case study can be found in Section 2.2.5). SIMDEUM® and SIMDEUM WW® were used to incorporate a stochastic wastewater discharge element into the model, based on occupancy statistics and appliance usage characteristics (Blokker et al., 2010; Blokker, 2011). Editing MATLAB® codes behind SIMDEUM® enabled integration with InfoWorks® ICM to produce a stochastic sewer model.

2.2.4.1 Household discharge modelling

SIMDEUM® was chosen for use in this study due to its capability to produce the discontinuous, randomised flow patterns, typical of wastewater networks. Accurate representation of wastewater flow is key when investigating flow changes within the sewer system. This software tool produces high-resolution household demand patterns at the spatial and temporal scales necessary for predicting flow changes as a result of water conservation. SIMDEUM® is based on a series of MATLAB® codes which mean it is possible to develop and adapt the software for new applications. SIMDEUM® generates household demand patterns based on the discharge probability of specific appliances, a thorough outline of the software can be found in Blokker et al. (2010). SIMDEUM WW® is an extension of the original SIMDEUM®, which converts the demand flow into a wastewater discharge pattern. Some appliances have similar demand and discharge patterns, such as a bathroom tap running to the drain, but a toilet or bath can discharge much faster than they are filled. Using the combination of SIMDEUM® and SIMDEUM WW® it was possible to calibrate the model input against water demand meters to produce likely discharge pulse flows into the sewer.

Calibration of SIMDEUM®/SIMDEUM WW®

SIMDEUM® was originally calibrated and validated for Dutch drinking water applications and therefore required adaptation of the input parameters to describe UK wastewater in this work. By adapting the input parameters that dictate the probability of an appliance discharging and the difference in occupancy it was possible to calibrate this stochastic model to generate random patterns that are likely of the studied catchment, as follows.

Calibration using water use trends and household meters

Data from household drinking water meters were used to calibrate the SIMDEUM® discharge profiles. These drinking water meters report an average daily household water use. Meter readings are recorded about every three months, and the average daily water use was found considering the duration between readings. Appliance usage distribution within the home was taken to be the UK average, see Figure 2.2-1 (Energy Saving Trust, 2013), and the per capita water consumption was derived from household meters (assuming 2.3 people per household). SIMDEUM® input parameters controlling frequency of appliance usage were manipulated to reflect the average water use (per capita), as reflected in the demand data. A 95% confidence interval was produced using historical water use data from these meters between 2010 and 2017, and error analysis between cumulative frequency plots (see Eq. (2.2-1)) facilitated comparison between water use distribution in the observed data and predicted water use.

$$\sum(Error)^2 = \sum_{i=0}^{n}\left(X_{i_{metered}} - X_{i_{predicted}}\right)^2 \qquad (2.2\text{-}1)$$

$$where, X_i = Number\ of\ households\ with\ water\ use\ inside\ interval, i$$

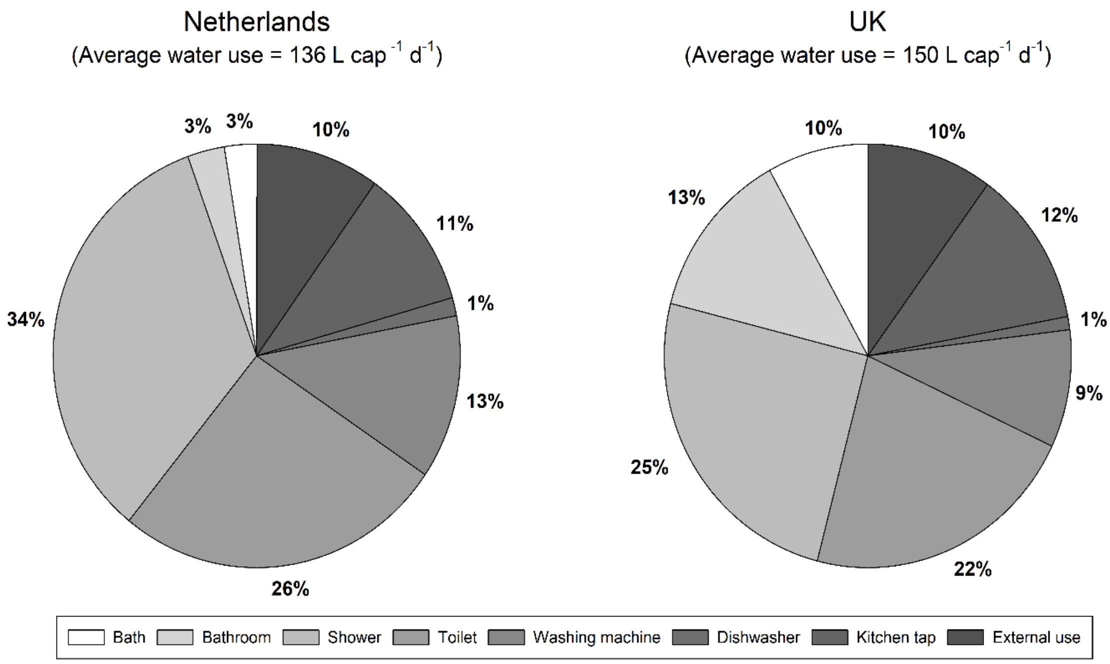

Figure 2.2-1. Proportion of household water that is used by appliances in the Netherlands and the United Kingdom (Blokker et al., 2010; Energy Saving Trust, 2013; WATERWISE, 2016)

Table 2.2-1 describes the average water utilisation per appliance in the water use scenarios discussed in this work. The Dutch average and eco household are default scenarios within the SIMDEUM® software. The usage profiles for Catchments A and B have been created for the studied catchment, described in Section 2.2.5, through the calibration process.

Table 2.2-1. Outline of appliance usage in SIMDEUM® scenarios. Catchments A and B are the UK based catchments modelled in this work and the appliance-specific water use has been defined through inspection of metered data and knowledge of appliance usage in the UK (Figure 2.2-1)

Appliance	Dutch Average	Catchment A	Catchment B	'Eco' household
	(Water used per appliance, L capita^{-1} day^{-1})			
Bath	3.5	6.4	10.4	
Bathroom tap	4.0	10.4	16.9	4.0
Dishwasher	1.6	0.8	1.3	0.2
Kitchen tap	14.8	9.6	15.6	11.7
*External/losses	13.4	8.0	13.0	
Shower	45.9	20.0	32.5	24.8
Toilet	35.4	17.6	28.6	6.0
Washing machine	14.2	7.2	11.7	0.3
Total	132.7	80.0	130.0	47.0

* External use is not included in the wastewater profile

Calibration using household occupancy data

SIMDEUM® is not based on measurements but rather parameters from statistical knowledge of human behaviour. Three household types are defined and statistics on the gender, age and employment composition are used within a Monte Carlo simulation to generate an overall distribution of household type. Discharge profiles are produced using occupancy statistics alongside appliance discharge probability. Further details on the development of this software can be found in Blokker et al. (2010). Figure 2.2-2 shows the average Dutch occupancy statistics that is the software default. The distribution of single, dual and family households are defined in the centre of Figure 2.2-2, and the typical composition parameters around the edges. Different usage habits create a unique stochastic household flow pattern depending which household type is chosen for simulation through the Monte Carlo step. Data describing household occupancy in the studied catchment was not available to the levels of detail shown in Figure 2.2-2, therefore discharge patterns were calibrated using only data on the division of household type (central pie chart in Figure 2.2-2). 2011 UK Census data (Office of National Statistics, 2011) for the studied catchment was used to define the proportion of single, dual and multi-occupancy households present. By changing the input variables within the SIMDEUM® .stats files, in line with the statistics presented in Table 2.2-2, it was possible to shift the division shown in the central pie chart (Figure 2.2-2) to better represent the demographic of the modelled catchment. This calibration therefore gives an accurate occupancy-based prediction of water use in the studied catchment.

Table 2.2-2. Differences in household occupancy between SIMDEUM® average and the case study

	One Person Households	Two person households	Family Households
SIMDEUM® Default	34.0%	30.0%	36.0%
Studied Catchment	25.7%	42.6%	31.7%

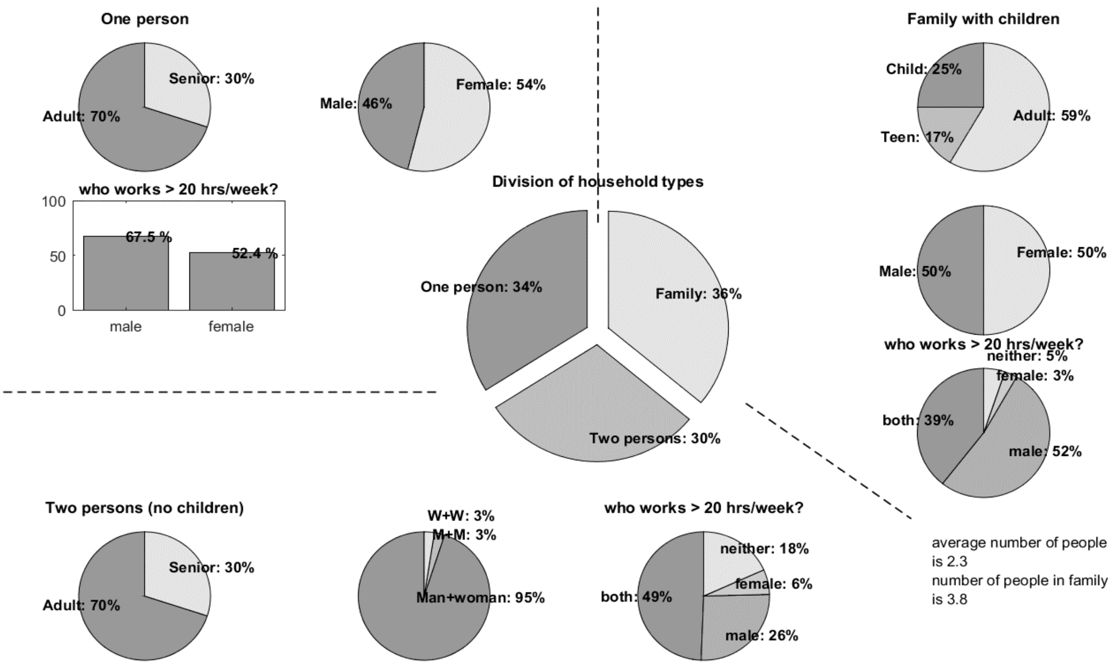

Figure 2.2-2. SIMDEUM® household occupancy data used in Monte Carlo simulation (Blokker et al., 2010)

2.2.4.2 Hydraulic sewer modelling

The sewer network studied, see Section 2.2.5, was modelled using InfoWorks® ICM (Sewer Edition; Innovyze Ltd, Oxfordshire). The outputs from the stochastic sewer model were validated using sewer flow meters. The hydraulic model was further tested with new input data to conduct some preliminary tests for future water use scenarios.

Preparing the network model for stochastic discharge patterns

The network model was based on asset data received from Wessex Water (Section 2.2.5) and modelled using InfoWorks® ICM (Sewer Edition; Innovyze Ltd, Oxfordshire). Wastewater discharge profiles, generated using the methodology described in Section 2.2.4.1, were used here as an input into the sewer model, using 5-minute intervals (this provided sufficient compromise between runtime and resolution). A MATLAB® code was built to convert the SIMDEUM WW® output results to match the import requirements of InfoWorks® ICM as domestic wastewater event files. Each of the household profiles were imported to InfoWorks® ICM via the InfoWorks® format .csv file. Each property was given its own subcatchment and was described using its unique stochastic wastewater profile, as discussed in Section 2.2.4.1. The simulation results time step was selected as 5-minutes so to agree with the input file resolution.

Hydraulic model validation

The hydraulic model output was validated through comparison with data obtained from flowmeters placed at the end of the study catchment which monitored flow, depth and velocity over a five-month period at the beginning of 2015. The flowmeters used were Detectronic MSFM (Multi-Sensor Flow Monitor) (Detectronic, 2018). These are microprocessor-controlled monitors measuring depth (using a differential pressure transducer) and velocity (using a velocity Doppler-shift transducer) with a probe immersed in the flow. The probe was placed on the invert of the incoming pipe (egg shaped pipe with height of 1250mm and 800mm width) 2750mm from the manhole cover. Depth (accuracy±0.2%) and velocity (accuracy±2.5%) readings were averaged over 2 min intervals. Following the removal of any erroneous results, flow results were produced using DARAS (Drainage and Rainfall Assessment Software) which is a computer program used for analysing large volumes of data and producing flow results from depth and velocity measurements for defined pipe shapes. Flow monitors were inspected weekly to check for sediment or ragging problems. Observing the 95% confidence interval for each weekday from the validation data enabled comparison with the sewer model output. For a map of the studied catchment and location of the flowmeters see Section 2.2.5.

Future scenario testing

The stochastic sewer model was developed for observing the impacts of wastewater reduction on the sewer system. In future, specific water use scenarios will be simulated based on predicted societal changes. As a preliminary study, the calibrated model input was replaced with the input of an 'eco' household. This water use scenario was developed in the work of Agudelo-Vera et al. (2014) and involves the adoption of innovative sanitation concepts, such as 1 L flush toilets and highly water efficient showers, washing machines and dishwashers. This eco household scenario generates a random selection of household discharge patterns based on the average water use of 47 L $capita^{-1}$ day^{-1}, the appliance usage distribution can be found in Table 1. The validated output was compared to the result with this reduced input. Flow, velocity and depth were compared at the catchment outfall. An assessment was also made in all pipes of the network to see whether this input change resulted in increased stagnation. Three different pipe sizes were present in the studied catchment: 100 mm, 150 mm, and 225mm (representing 52%, 26% and 22% of the total pipe length, respectively). These size classes had average slopes of 1:61 (ranging 1:346–1:2), 1:46 (ranging from 1:105 to 1:9) and 1:206 (ranging from 1:1042 to 1:7), respectively. The three pipe classes were analysed separately to assess the time each of the pipe classes spent under stagnation. Time was recorded for the duration when flow was equal to 0 m^3 s^{-1}, velocity was equal to 0 ms^{-1} and depth was equal to or less than 0.01 m, as this is the minimum depth required to ensure the stability of the InfoWorks ICM® model. Time spent below these thresholds was compared for the continuous, present day stochastic model and the future, eco model.

2.2.5 Case study

2.2.5.1 Description of the modelled catchments

The catchment studied is a residential, separated sewer network (i.e. excludes storm water) within the Wessex Water region of the UK. A map of the catchment is shown in Figure 2.2-3. The area marked ‘Catchment A’ serves around 200 households and was divided into smaller subcatchments for demographic and water use analysis. Average water use was found to be 80 L capita^{-1} day^{-1} in Catchment A (assuming 2.3 people per household), where metered data was available for 57% of the households. Catchment B represents a newer development in which 99% of the households had a water meter. The inhabitants of this catchment have an average water use of 130 L capita^{-1} day^{-1} (assuming 2.3 people per household). Due to the difference in water use between Catchments A and B, wastewater generation patterns were developed separately (Section 2.2.4.1). Table 2.2-1 describes the average water use per appliance used in developing the wastewater discharge profiles for each catchment. Catchments A and B have a combined size of 899 households and a combined average water use of 283 L household^{-1} day^{-1}. A flow meter was installed in the sewer at location FM14 (see Figure 2.2-3).

The sewer was modelled, in most cases, from the property boundary based on the available knowledge of lateral connections to the sewer. Known pipe locations and gradients were taken from the original model and the locations of some up-catchment private sewers were assumed with ground levels inferred from a LIDAR ground model, obtained through a Wessex Water private charter. The unknown invert levels were inferred assuming that the pipe gradient was equal to that to which it connects downstream. Head loss coefficients were inferred through the InfoWorks® ICM model based on pipe material (Colebrook-White coefficients of 1.5 mm for the top two thirds of the pipe and 3mm for the bottom third) and connection angles.

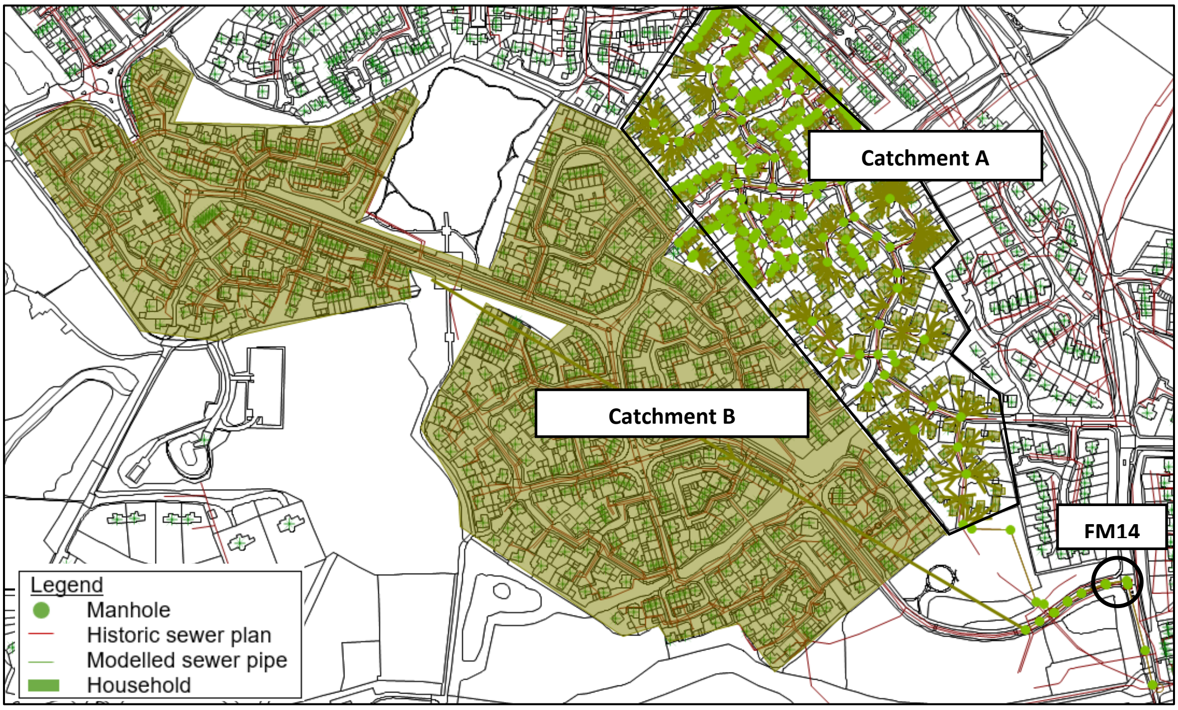

Figure 2.2-3. Map of modelled sewer catchment and the flow meter (FM14)

2.2.6 Results and discussion

2.2.6.1 Calibration of stochastic discharge model to UK situation

Calibrating stochastic household discharge patterns

Figure 2.2-4 shows a cumulative frequency plot of the simulated and measured water demand of different scenarios. It also shows the calibrated frequency plot for the studied catchment, based on the comparison of the SIMDEUM® stochastic patterns with observed data from household water meters. The distribution in water use from households in Catchment A was found to lie between that of two SIMDEUM® default scenarios, the average Dutch household and the 'eco' low water use household. By following the steps described in Section 2.2.4.1, it was possible to produce a new set of discharge patterns that agree well with the observed data. As it can be seen from Figure 2.2-4, the calibrated discharge patterns lie mostly within the 95% confidence interval of the metered data.

SIMDEUM® is however less accurate at predicting the number of low water use households. This calibration is based on average water use between meter readings, which could be several months apart. Therefore, the true dynamics in daily water use will be averaged over a period of time. With regard to the households using less than 75 L household^{-1} day^{-1}, it may be the case that these are single person households in which the occupant is often away from home and therefore the annual averaged consumption would be more conservative than the actual water demand when the person is at home. SIMDEUM® also assumes full occupancy of households throughout the year; therefore lower water use in the holiday season is not accounted for.

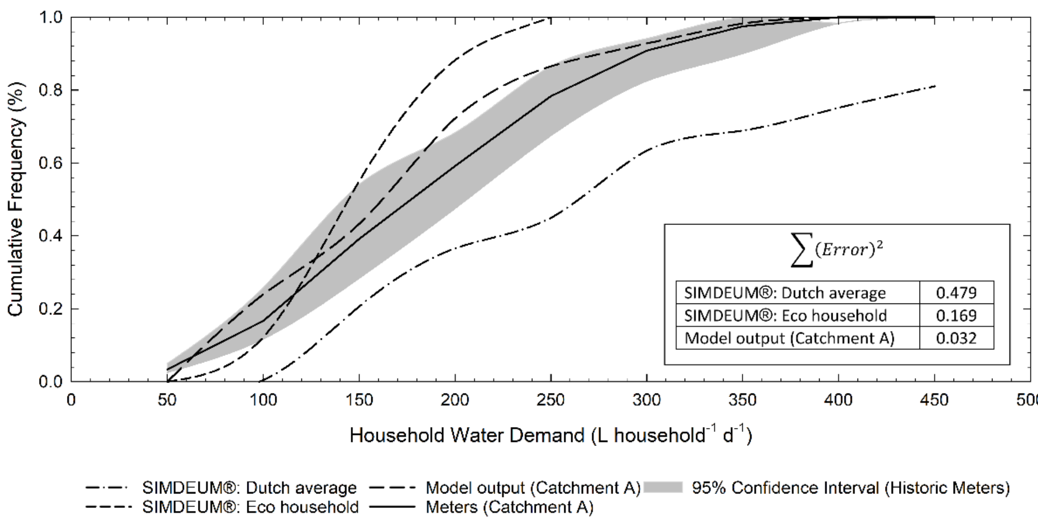

Figure 2.2-4. Performance of SIMDEUM calibration for use in a UK stochastic sewer input model

A stochastic sewer model

By importing the calibrated, stochastic profiles into the sewer network model within InfoWorks® ICM, it was possible to observe the difference a stochastic sewer model can make when compared to traditional sewer modelling methods. Fig 2.2-5 shows the resulting flow, depth and velocity profiles in a selection of pipes in the Catchment A sewer network. It is a common assumption in sewer modelling that continuous diurnal discharge patterns are produced by each household (left side of Figure 2.2-5). The stochastic model (right side of Figure 2.2-5) is a more accurate representation of the real situation; short, sharp discharge peaks eventually culminating in quasi-continuous flow downstream. The traditional continuous case, utilised by the water company, was developed assuming average water use of 155 L capita^{-1} day^{-1} and the volume was fitted to a diurnal pattern equal to that measured at a downstream pumping station. The average water use in the continuous model has been adapted to match the average water use of the study Catchments A and B (80 and 130 L capita^{-1} day^{-1} respectively). By comparing the continuous and stochastic outputs for three pipes in Catchment A (Figure 2.2-5), it can be seen that the daily peaks and troughs are much more defined in the stochastic case. Pipes lower down the catchment follow a similar diurnal pattern to the continuous case, but the morning peak is higher and the flow through the day is much reduced. The up-catchment pipe shows much higher flows and velocities than are predicted by the continuous model. This highlights the importance of using stochastic discharge models for accurate sewer modelling applications. The stochastic model is superior as it allows observation of intermittent flow in upstream pipes, this will allow the analysis of the risks of stagnation and flow surges that are more likely in a real system.

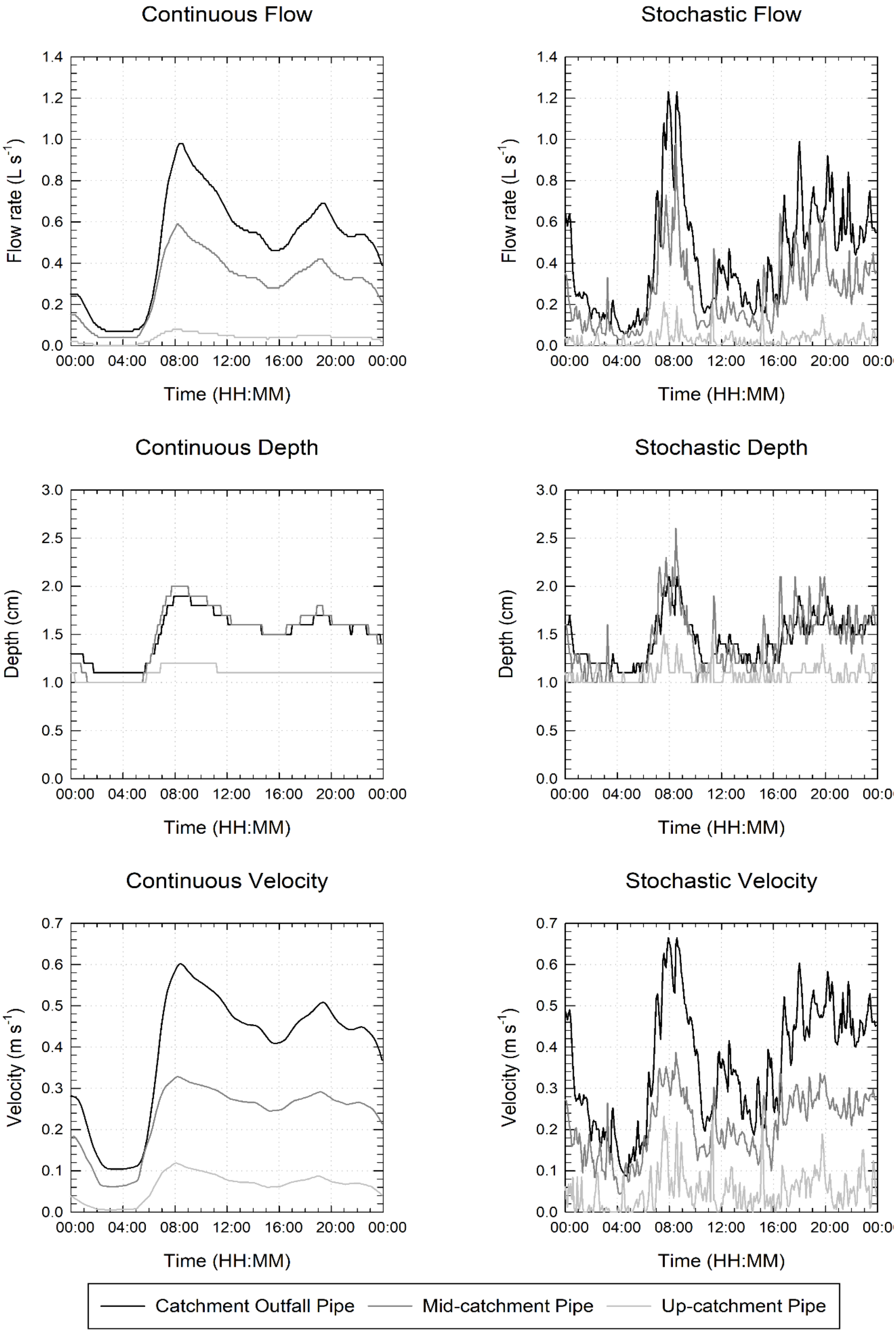

Figure 2.2-5. A comparison between continuous and stochastically generated wastewater profiles in selected network pipes (Catchment A). Note: the stochastic plots demonstrate a snapshot of one run scenario.

2.2.6.2 Validation of the stochastic flow model

The model output data was validated using data collected with flowmeter FM14 at the outfall of the catchment area (see Figure 2.2-3). A visual comparison between the observed data and the simulation results can be seen in Figure 2.2-6, where flow, depth and velocity measurements for consecutive weekdays are presented. The stochastic flow model largely correlates with the measured data; however, the evening peaks seem to be shallower but extend later into the night than the observed case. This is likely to be due to the difference between daily routines in the catchment area versus those assumed in the simulations. SIMDEUM® was developed and validated using in-depth data on how people spend their time, specifically their presence at home. The people living in this catchment of the UK seem to have different habits, perhaps going to bed earlier and not choosing to use so many appliances at night. A closer fit could be achieved by surveying precise occupant behaviour in the area but as the purpose of this analysis is to investigate effects of water conservation in a sewer it is not of interest to the authors that the profiles match exactly. The flowrate prediction is mostly within the 95% confidence interval of the flow survey data so it can be deemed reliable for further application of the model. Depth and velocity predictions are a reasonable fit to the observed data, although depth is a bit high and velocity a bit low. The calculation of these parameters is dependent on the friction coefficients within the pipe network. The friction coefficients were assumed based on pipe material; slope and the angle of incidence of the joining pipe were matched as closely as possible to the actual situation in the catchment but the true asset conditions were not known.

It can be observed from Figure 2.2-6 that the continuous profile captures the morning peak in flow well but overestimates the flow throughout the day and offers a modest evening prediction. This suggests that the continuous profile was created using data measured further down the catchment than the flowmeter FM14 and therefore the true extremities of the diurnal pattern were lost. As has been stated previously, the extremities in flow will be very important when modelling the effects of water conservation so this confirms that the stochastic model is superior to the traditional continuous prediction.

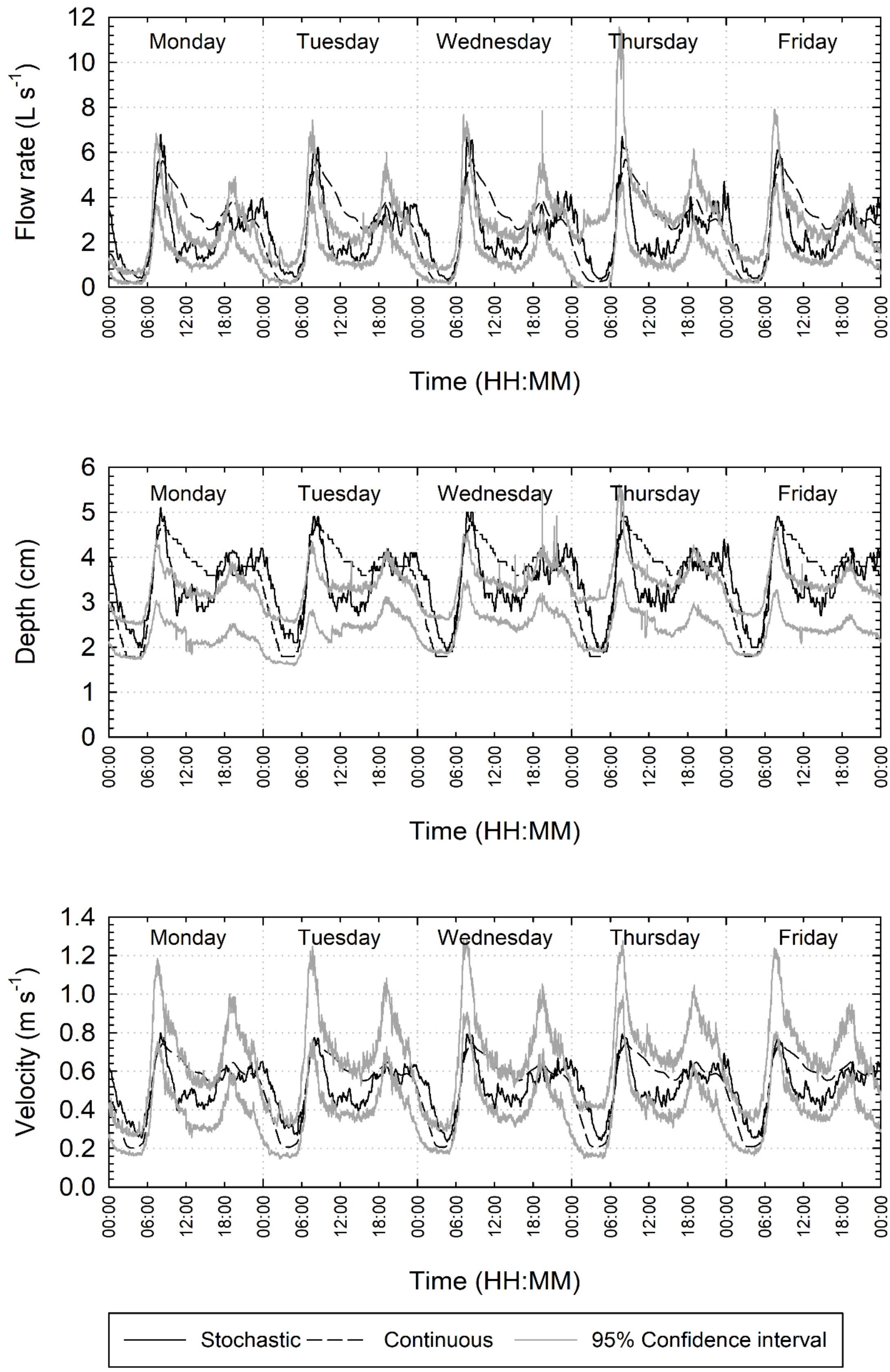

Figure 2.2-6. Monday-Friday validation of sewer model using flow, depth and velocity monitoring at the exit of the catchment (FM14). Note: the stochastic profile demonstrates a snapshot of one run scenario.

2.2.6.3 Early assessment of hydraulic sewer effects as a result of water conservation

Some preliminary assessment of how low water use may affect sewage flow has been completed, and this was compared with the standard calibrated model in Figure 2.2-7. The low water use scenario presented is a SIMDEUM® default scenario, here named 'Stochastic - Eco', this is the same 'eco' house scenario as mentioned previously. It can be seen from the plots that flow is not reduced equally throughout the day. This is thought to be due to major water savings gained by certain appliances in the 'eco' scenario compared to the 'present' scenario. It is likely that the large reduction in toilet flush volume and increased shower efficiency are responsible for the large reduction in morning peak. There is also a large reduction in late night use, this is due to the reduction in dishwasher and washing machine usage volumes. Other comparisons between the present appliances and the eco case can be found in Table 2.2-1. At the catchment outfall the major flow effect is the reduction of the morning peak, however the effect on flow cannot be translated into an effect on velocity. If velocity is the driving force for sediment transport, as is always assumed, there is a smaller effect than is suggested by the flow reduction. The biggest effect of reduced flow is the reduction in water depth, not so much in the velocity (the head loss stays the same, equal to the pipe slope). British standards suggest a minimum of $0.7ms^{-1}$ at peak flow to ensure self-cleansing (Butler and Davies, 2011). In this low water use scenario these criteria would only just be met at the catchment outfall, so if this peak is required for solids movement throughout the network it may represent an issue upstream. The 'eco' scenario sees overnight flow drop as low as 20% of the 'present' case and the morning peak flow drops to ~60%. The mid-day low point sees water use drop to 30%, whereas the evening profile remains more similar for both cases. Depth and velocity in the 'eco' case drop to 60–80% of the 'present' case for most of the day; however, evening results are less effected. It is worth noting that to attempt this kind of assessment with a continuous model you would need to apply a reduction factor to the entire demand pattern which would give different and inaccurate results.

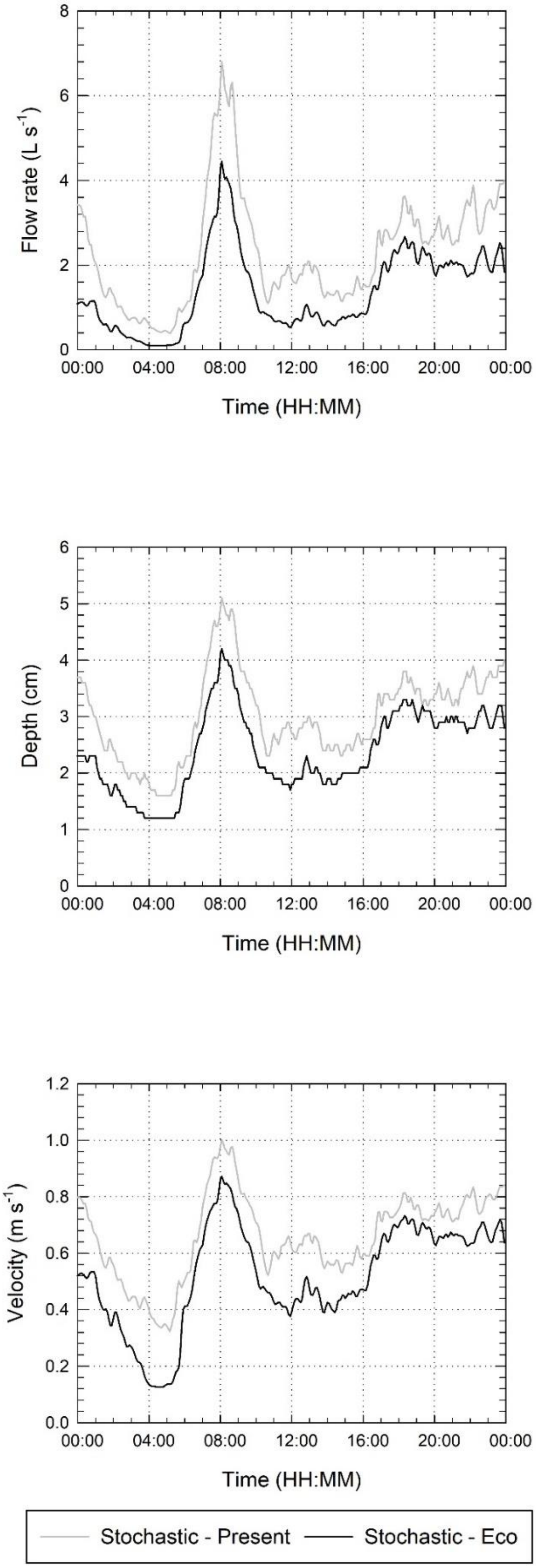

Figure 2.2-7. Daily variation in flow, depth and velocity at the outfall - comparing present and future water use. Note: these stochastic outputs demonstrate a snapshot from one possible run scenario.

The effects of lower water use have been thought to be more severe upstream, in smaller pipes, where flow is lower and more intermittent (Penn et al., 2014). Figure 2.2-8 shows a comparison of how water flow varies, between the present-day case and the eco case, in an upstream pipe (150 mm) with 11 household connections. This cannot be compared peak-for-peak due to its stochastic nature, but it is apparent that the stochastic eco model has substantially smaller peaks and fewer of them. An important concern when it comes to increased water conservation is the risk of increased sediment deposition. Low velocities and water depth could lead to partial blockage that reduces flow and encourages further sediment formation. Apart from the risk of blockage, sediments deposited in sewer pipes can degrade anaerobically and thus give rise to harmful gas formation.

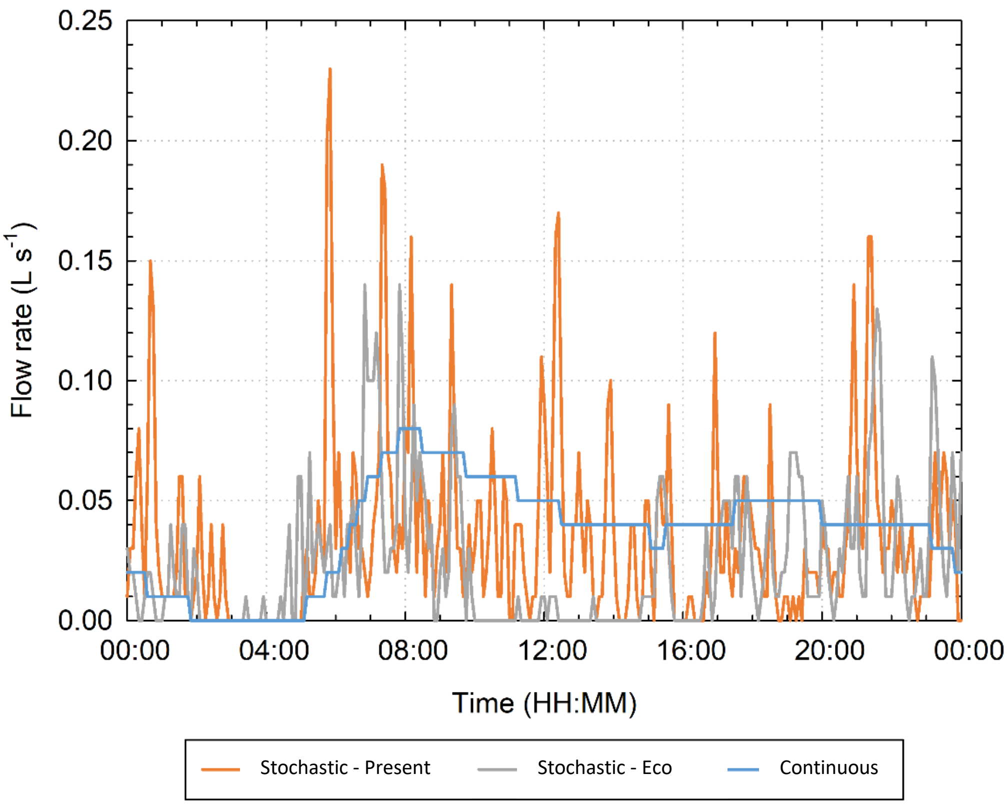

Figure 2.2-8. Flow in an upstream pipe – a comparison between continuous, stochastic present and future water use modelling scenarios – 11 household connections. Note: the stochastic profiles demonstrate a snapshot from one possible run scenario.

Table 2.2-3 shows the average time spent in stagnation for both stochastic cases ('present' and 'eco') as well as the continuous modelling method. This confirms that low flow is more of a risk in the smaller pipes within the network. The difference in stagnation between the 'present' and 'eco' cases is largest in the 150mm pipes, whereas the effect on household laterals is less. This suggests that household laterals that are mostly in a state of no/low flow currently will remain similar, whereas pipes of larger diameter that currently collect from multiple households will experience increased intermittencies in flow. Levels of stagnation in both stochastic cases are significantly greater than the continuous modelling case. This would be expected but poses questions as to whether the peaks are large enough to flush out solid build-up. The network has not experienced many blocking problems in the past and does not have a frequent cleaning regime; hence, it may be assumed that the flow peaks in the validated 'present' case are sufficient to prevent build-up. However, further research needs to be conducted to conclude whether the smaller peaks predicted by the 'eco' case would be large enough to shift debris.

Table 2.2-3. Analysis of stagnation in sewers as a result of changes in water use

(Shading legend: Shortest time → Longest time)

	Threshold value	Pipe diameter (mm)	Continuous	Stochastic Present	Stochastic Eco
			Avg. time per day in stagnation (hr)		
Flow ($m^3 s^{-1}$)	0	100	10.0	18.7	19.5
		150	2.9	6.2	9.2
		225	0.0	0.0	0.0
Velocity (m/s)	0	100	0.6	14.0	14.1
		150	0.0	2.8	4.1
		225	0.0	0.0	0.0
Depth (m)	0.01	100	8.2	19.5	20.5
		150	3.1	12.3	14.5
		225	0.0	0.0	0.2

2.2.7 Conclusions

It is important to understand the effect that significant water conservation will have on sewerage systems and how this could help (re)design better networks to reap the potential benefits. A stochastic household wastewater discharge model has been developed and calibrated to achieve this. The model has been developed considering a separated drainage system, although it could also be used for combined sewer systems where rainfall events would simply add on to the stochastic DWF pattern. The model gives accurate prediction of the diurnal patterns of sewage discharge at household level in residential areas when compared to flow, velocity and depth data from a downstream flow meter.

A stochastic discharge element has been used in combination with a sewer network model to produce a stochastic sewer model for hydraulic flow prediction. This model has been validated against flow data collected at the outfall of the analysed real catchment. The results obtained demonstrate that this model enables more accurate flow, depth and velocity predictions than the traditional continuous sewer model.

Application of the stochastic sewer model to the analysed case study revealed that a low water use scenario reduced the overnight and daytime flow by up to 80% whereas evening flows were largely similar. Stagnation times remained similar in household laterals but longer stagnation times were observed in the street scale pipes (150 mm) than in the 'present' water use scenario.

This model will be used further to simulate future water use scenarios to accurately predict changes to flow velocity and pollutant concentration due to water conservation. Following the hydraulic model validation, the model will be extended to include sewer water quality. This will further utilise the capabilities of SIMDEUM WW® to generate stochastic pollutant profiles for household discharge under dry weather conditions. Within SIMDEUM® it is known which appliances generate wastewater flows, and thus it is possible to attribute water quality parameters to each type of discharge. This allows discharge simulation of various wastewater characteristics (e.g. temperature, organics, pharmaceuticals and nutrients) (Pieterse-Quirijns et al., 2012). By integrating this output with InfoWorks® ICM, built-in water quality models will be used to assess organic/nutrient concentrations and sediment build-up for various wastewater scenarios. In turn this may identify opportunities/need for upstream treatment interventions.

2.2.8 Declaration of interests

None declared.

2.2.9 CRediT authorship contribution statement

O. Bailey: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing - original draft, Writing - review & editing. **T.C. Arnot**: Supervision, Writing - review & editing, Funding acquisition**. E.J.M. Blokker**: Software, Writing - review & editing. **Z. Kapelan**: Writing - review & editing. **J. Vreeburg**: Writing - review & editing. **J.A.M.H. Hofman**: Supervision, Writing - review & editing, Funding acquisition.

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Chapter 3

Predicting impacts of water conservation with a stochastic sewer model

This work was published in Water Science and Technology (IWA) in January 2020.

This paper was subsequently selected as 'Editor's Choice' with the following reasoning: "I have chosen for my Editor Choice Predicting impacts of water conservation with a stochastic sewer model. This is a great example of why we need to understand all the consequences of our good intentions (the side effects as well as the desired effects) but also an example of how we can deal with unintended consequences. Their mere existence is not a good reason not to pursue the right course of action overall. Industry anecdotes about how water conservation is damaging sewer system operation abound, but this paper shows how we can adapt to changes - as we must, if we are going to adjust our civilizations to the new climate in which we now live." Jo Burgess, Editor.

Bailey, O., Arnot, T. C., Blokker, E. J. M., Kapelan, Z., Hofman, J. A. M. H., 2019. *Predicting impacts of water conservation with a stochastic sewer model.* Water Science and Technology **80**(11): 2148-2157. DOI: https://doi.org/10.2166/wst.2020.031

3.1 Context

The previous chapter of this thesis showed the development of the hydraulic aspect of the stochastic sewer model and demonstrated its use to observe impacts on flowrate, velocity and flow depth. However, the model is still not capable of predicting the wastewater concentration that has been shown to be such an important factor in resource recovery. Neither is it clear how wastewater flow and concentration differ for a variety of future scenarios.

The appliance-specific nature of the SIMDEUM®/SIMDEUM WW® software package means it also presents the opportunity to incorporate pollutant discharge concentration linked each appliance. The water discharged from a shower is very different from that discharged from a toilet or a washing machine. Modelled wastewater quality in this way could give a much more detailed look into how future water use changes would affect wastewater concentration. Better knowledge of wastewater quality could help define treatment and resource recovery options but also the likelihood of solids being effectively transported. The following paper aims to define wastewater quality profiles for typical household water-using appliances and use SIMDEUM WW® to generate appliance-specific wastewater discharge profiles. This wastewater discharge information was included as an input to the InfoWorks® ICM water quality model, through developing a new module of SIMDEUM WW®, to predict time-varying wastewater quality through the sewer.

This chapter is submitted in an alternative format in line with Appendix 6A of the “Specifications for Higher Degree Theses and Portfolios” as required by the University of Bath.

The work completed in this paper was conducted by the author with the exception of the following:

- The development of the water use scenarios used in this would were developed by Artesia Consulting.

Statement of Authorship

This declaration concerns the article entitled:	
Predicting Impacts of Water Conservation with a Stochastic Sewer Model	

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Candidate's contribution to the paper (provide details, and also indicate as a percentage)	The candidate contributed to / considerably contributed to / predominantly executed the… **Formulation of ideas:** Fully executed by candidate Supervision provided by Jan Hofman and Tom Arnot. **Design of methodology:** Fully executed by candidate Supervision provided by Jan Hofman and Tom Arnot. **Experimental work:** Fully executed by candidate with the exception of the following: - The development of the water use scenarios used in this would were developed by Artesia Consulting. Supervision provided by Jan Hofman and Tom Arnot. Software guidance provided by Mirjam Blokker. **Presentation of data in journal format:** Fully executed by candidate. Review and editing provided by Jan Hofman, Tom Arnot, Mirjam Blokker and Zoran Kapelan.
Statement from Candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.

Signed	Bailey	**Date**	16/07/2020

3.2 Water Science and Technology paper

Predicting impacts of water conservation with a stochastic sewer model

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3.2.1 Abstract

Population growth and climate change put strain on water resources; hence, there are growing initiatives to reduce water use. Reducing household water use will likely reduce sewer input. This work demonstrates the use of a stochastic sewer model to quantify the effect water conservation has on sewer hydraulics and wastewater concentration. Probabilistic discharge patterns have been developed using SIMDEUM WW® and fed into hydraulic modelling software InfoWorks® ICM to produce likely flow and quality profiles for five future water use scenarios. The scenarios tested were developed to outline how commercial and political factors may change water use in future. Scenario testing revealed that 15-60% water reduction reflected a 1-48% drop in the morning peak flow. The water use reduction showed to increase wastewater concentrations of COD, TKN and TPH by 55-180%, 19-116% and 30-206% respectively. The sewer flow model was developed, calibrated and validated using a case study in the Wessex Water region of the UK and all future scenarios were compared to the validated baseline case. This wastewater flow and quality model allows scenario testing which could help redesign future sewer networks to better prepare for water conservation strategies.

3.2.2 Keywords

Sewer Design; Stochastic Sewer Modelling; Future water use; Wastewater Quality Modelling; Wastewater concentration; Appliance-specific discharge

3.2.3 Introduction

Population growth, urbanisation and climate change place a strain on water resources and in response, there is mounting pressure to reduce household water use. UK Water Industry Research (UKWIR) (2016) have stated the aim to halve water abstraction by 2050. This will significantly reduce inflow into sewer systems and increase wastewater concentration. More effective sewage treatment and resource recovery could result from higher wastewater concentrations (Verstraete & Vlaeminck, 2011), however, sewer transport efficiency may be affected (Parkinson et al, 2005; Penn et al, 2013). This work outlines the development of a stochastic sewer model which enables accurate predictions of dynamic flow and pollutant changes in the wastewater network resulting from widespread water conservation.

Water consumption is likely to reduce significantly into the future and this is likely to increase wastewater concentration. Aside from saving water, increasing wastewater concentration is also an attractive concept for sustainability. Recovering resources from waste is becoming much more interesting for water companies worldwide (BillandBiorefinery, 2017; GENeco, 2016; UKWIR, 2016; WssTp, 2016). Wastewater can be quite concentrated at the household level but as it travels through the sewer network it can become significantly diluted by rainwater and infiltrating groundwater. Research has been conducted into the options that can catch wastewater in this concentrated form and make resource recovery from wastewater more effective (Diamantis et al., 2013; Hernández Leal et al., 2010; Tolksdorf and Cornel, 2017; Verstraete and Vlaeminck, 2011). Presented options range from the decentralisation of wastewater treatment to re-concentration at the wastewater treatment plant (WWTP). It was presented in Verstraete and Vlaeminck (2011) that a preferable option would be to prevent dilution of wastewater in the sewer via the use of separated sewer systems, reduced infiltration rates or addition of kitchen waste to sewage to boost nutrient concentrations. It was suggested that reducing water consumption by 25% in a separate system could increase wastewater concentration by about 190%.

Increasing populations and urbanisation mean that there is rising pressure on existing wastewater infrastructure. In some cases, this can cause the system to overflow or call for a new expansion of the sewerage system, for example, the Tideway tunnel in London (Tideway, 2019). This multi-billion-pound project aims to expand London's sewer capacity to cope with the dramatic population increase since the installation of the sewers in the late 19th century. Reducing water consumption could take the pressure off existing infrastructure and extend its lifetime, thus reducing the need for costly expansions and replacements. Wastewater treatment becomes more efficient at higher concentrations (DeZellar and Maier, 1980; Parkinson, 1999; Royal Haskoning DHV, 2017) producing a higher quality effluent and reducing the required size of the treatment process.

A stochastic flow model to assess the impact of water conservation on the sewer was presented by Bailey et al. (2019). In this paper, the extension of that model to include wastewater pollutant concentrations is described. Parkinson et al. (2005) utilised the Hydroworks® software to predict CSO potency under various water conservation measures. They used a deterministic input profile for domestic wastewater generation and promoted the sustainability of rainwater reuse as a future strategy because it ensured the dilution of wastewater in comparison to other water conservation strategies (i.e. reduced potency CSO's and sedimentation). Penn et al. (2013) furthered this by building a flow and quality model to assess the effects of greywater reuse on sewer systems in Israel. The model based in the SIMBA® simulation system utilised typical daily flow patterns per appliance, derived from the work of Butler et al. (1995), Friedler et al. (1996) and Almeida et al. (1999). The derivation of the flow patterns and pollutographs used were described in the work by Penn et al. (2012). When testing the effects of greywater reuse (GWR) scenarios on the sewer it was found that pollutant concentrations increased with higher penetration of GWR and a further increase was discovered with water-efficient toilets. Pollutant increases reported were 6-42% COD, 7-73% TSS, 9-57% NH4-N and 7-52% PO4-P for flow decreases of 8-41% (Penn et al., 2013). The simulated concentration was found to be 60-100% of the potential increase (as indicated by the mass balance) due to the treatment of the greywater before reuse.

SIMDEUM® (Watershare, 2016) is a tool that utilises input parameters linked to appliance usage, household composition and consumer water use behaviour to generate stochastic water demand profiles (Blokker et al., 2010). SIMDEUM® provides household profiles with small temporal (1 s) and spatial (customer tap) scales, this allows it to be used to assess appliance specific changes in the water network, i.e. without a predetermined appliance usage pattern. Bailey et al. (2019) calibrated SIMDEUM® to be used for predicting water use patterns of consumers in the UK. These demand patterns were then adapted to represent sewer flow using SIMDEUM WW®. This was a development of SIMDEUM® that describes wastewater discharge, including thermal and nutrient loads (Pieterse-Quirijns et al., 2012). Some household appliances have a different discharge pattern than their demand pattern, e.g. dishwashers and washing machines take in water at the start of the wash cycle and discharge it at the end, which could be some time later. The average nutrient concentration and water temperature associated with a certain appliance are also incorporated into the discharge profile.

As mentioned previously, the work presented in this paper describes the extension of a stochastic sewer model developed by Bailey et al. (2019) to include wastewater quality. This model has been used in order to assess the flow and concentration changes that may arise in certain future water use scenarios. It was based on SIMDEUM WW® household discharge patterns, as input to a hydraulic and water quality sewer network model in InfoWorks® ICM. The flow model was tested and validated for a case study provided by Wessex Water, a UK-based water utility company. Appliance water quality attributes (from published literature) have been linked with the validated flow to produce a water quality prediction, this output has yet to be validated. The paper is organised as follows; the methodology behind the wastewater quality profiling and scenario testing has been outlined with a brief description of the case study simulated using the model, more detail is available in the work of Bailey et al. (2019). The outputs from modelling the water conservation scenarios have been presented and analysed. This is followed by the key conclusions to be made from this work.

3.2.4 Methodology

This work utilises the model presented in Bailey et al. (2019), in which Infoworks® ICM (Sewer Edition; Innovyze Ltd, Oxfordshire) was used to simulate a sewer network within the Wessex Water region of the UK. Stochastic discharge patterns were produced using SIMDEUM® and SIMDEUM WW® (Blokker, 2011; Blokker et al., 2010) and incorporated within the InfoWorks® ICM model by way of editing MATLAB® codes behind SIMDEUM®. This made it possible to produce outputs in the correct format required by InfoWorks® ICM. SIMDEUM WW® (Pieterse-Quirijns et al, 2012) was used to incorporate stochastic wastewater quality patterns into the sewer model that are linked to specific appliance discharges. Five future water use scenarios were subsequently simulated within the validated model and flow and concentration effects were analysed.

3.2.4.1 Household discharge modelling

<u>Hydraulic discharge</u>

SIMDEUM® is a software that generates probabilistic household demand patterns based on statistical information about inhabitants and appliance usage (Blokker et al., 2010). Bailey et al. (2019) describe how SIMDEUM® discharge patterns were adapted and calibrated using the 2011 UK Census (ONS, 2011) and household meter data (Wessex Water, 2010-2017) to accurately represent the hydraulic sewer wastewater input.

<u>Water quality loading</u>

Following the development of the flow discharges to the sewer, SIMDEUM WW® was used to associate water quality to the stochastic flow patterns. SIMDEUM® produces flow patterns on an appliance-specific basis so this enables a certain water quality to be attributed to each appliance discharge. Average values for pollutants discharged by typical household appliances were found through a review of relevant literature. Most values were taken from (Parkinson et al., 2005) as this study included a review of other literature to conclude typical appliance concentrations (Butler et al., 1995; Parkinson, 1999; Siegrist et al., 1976; Surendran, 1998). Appliance concentrations were converted into an expected pollutant mass per discharge by multiplying the concentration by the water volume utilised by each appliance. Toilet concentration values, as well as the appliance discharge temperatures, were taken from the work of Blokker and Agudelo-Vera (2015). The toilet pollutant quantities were found by taking the average mass discharge from toilets a variety of toilet flush volumes (2/4 L, 6 L, 7.5 L and 9 L). To account for the possibility of GWR, input water quality was derived from the work of Penn et al. (2012) and added to the previously derived appliance discharge quality. The derived pollutant quantities can be found in Table 3.2-1.

Table 3.2-1. Appliance-specific discharge parameters used in the improved SIMDEUM WW® wastewater quality profiles. Pollutant concentrations of COD (chemical oxygen demand), TKN (total Kjeldahl Nitrogen), TPH (total phosphorus) and TSS (total suspended solids) are shown alongside discharge water temperature. Note: where appliance discharge includes multiple cycles of different temperatures the temperature of each cycle is shown in square brackets.

Appliance	**Temp. (^{o}C)**	**Sewage Quality (g use^{-1})**				**Explanation**
		COD	TKN	TPH	TSS	
Bath	36	25.90	0.85	0.15	8.88	Parkinson (1999), Parkinson et al. (2005)
Shower	35	12.60	0.49	0.07	4.32	Parkinson (1999), Parkinson et al. (2005)
Bathroom tap	40	1.48	0.04	0.14	0.56	Parkinson (1999), Parkinson et al. (2005)
Kitchen tap	40	7.48	0.35	0.28	4.68	Parkinson (1999), Parkinson et al. (2005)
Dishwasher	35	30.00	1.35	2.04	13.20	Parkinson (1999), Parkinson et al. (2005)
- With GWR		*31.47*	*1.50*	*2.34*	*14.31*	*Derived from effluent in Penn et al. (2012)*
Washing machine	[35,35,35,45]	65.25	0.68	1.26	17.10	Parkinson (1999), Parkinson et al. (2005)
- With GWR		*69.40*	*0.78*	*1.47*	*17.88*	*Derived from effluent in Penn et al. (2012)*
Toilet	20	11.22	1.99	0.25	3.04	Derived from Blokker & Agudelo-Vera (2015)
- With GWR		*11.48*	*2.00*	*0.26*	*3.09*	*Derived from effluent in Penn et al. (2012)*

3.2.4.2 Stochastic sewer model

InfoWorks® ICM (Sewer Edition; Innovyze Ltd, Oxfordshire) was used to simulate the flow and water quality through the case study sewer system. The hydraulic aspect of the sewer model was validated in the work of Bailey et al. (2019) using flow, depth and velocity data measured at the catchment outfall. The wastewater quality aspect of the Infoworks® ICM model occurs in parallel to the hydraulic model, transporting determinants and sediment through the drainage system. At each time step, the network model calculates the concentration of dissolved pollutants and suspended sediment at all the nodes using a conservation of mass equation. Then the conduit model calculates the concentration of dissolved pollutants and suspended sediment as well as the erosion and deposition of sediment in each conduit. The simulation time step in this work was set to 1-minute but results were output every 5-minutes as this provided sufficient compromise between runtime and resolution. Note that in this work, the modelling of sediment was not included, all wastewater quality determinants were modelled as dissolved pollutants and solids modelling has been highlighted as a topic for future work. Stochastic changes in wastewater concentration were imported into InfoWorks® ICM by means of a .csv file that was created in the correct format to produce a time-varying domestic wastewater event file (using 5-minute discharge intervals). Each property in the network has a unique flow and associated wastewater concentration input to the sewer system. In this work, wastewater determinants were modelled as dissolved pollutants due to an error in the InfoWorks® ICM software that fails to recognise time-varying solids input. The authors have been advised that this error will be corrected in the future update of InfoWorks® ICM.

3.2.4.3 Case study

The catchment used for this study was a residential, separated sewer network (i.e. excludes storm water) within the Wessex Water region of the UK. It comprises 899 households which have a combined average water use of 283 L household^{-1} day^{-1}, based on the population that have a household water meter installed (90% properties). This equates to 123 L cap^{-1} d^{-1} (when assuming 2.3 people per household). The catchment includes a combination of PVC, clay and concrete pipes a range in sizes of 100 mm, 150 mm, and 225mm (representing 52 %, 26 % and 22 % of the total pipe length, respectively). Each size class had the average slope of 1:61 (ranging 1:346 to 1:2), 1:46 (ranging from 1:105 to 1:9) and 1:206 (ranging from 1:1042 to 1:7, respectively. Further details of the studied catchment, as well as calibration and validation of the flow model, can be found in Bailey et al. (2019).

3.2.4.4 Future scenario testing

The purpose of developing the stochastic sewer model described in this work was to assess the potential effects that water conservation measures could have on wastewater flow and concentration. As the flow model has shown to represent the current sewer well, it can now be used to investigate the effects of potential future scenarios. Artesia Consulting has developed five potential water use scenarios for the UK in 2065 (Artesia, 2018), this was on the behalf of the UK Water Services Regulation authority (OFWAT). These scenarios are based on political and consumer changes in the UK water sector. They range from a very modest reduction over the next 50 years, which is the current ambition of the sector, to the dramatic shift in water use represented by a surge in water efficient appliances. Each of the five scenarios have been described in Table 3.2-2.

Table 3.2-2. Future scenario description – scenarios were produced by Artesia Consulting on behalf of OFWAT (Artesia, 2018)

Scenario	Demand* (L cap^{-1} d^{-1})	Description
S1 – Current ambition	105	Reasonable progress with public awareness and water efficient devices. *Changes to micro-components include* reduction in bath use, shower duration, replacement of older toilets.
S2 – Unfocused frugality	86	The public do not consider water scarcity as a problem, limited regulatory intervention, technology fails to deliver efficiency. *Changes to micro-components include* reduced shower frequency, reduced toilet flush frequency and volume, more efficient use of taps, washing machines and dishwashers (eco-cycles).
S3 – Localised sustainability	62	Water scarcity widely recognised as an important issue, widespread competition in the water market. *Changes to micro-components include* 1.5 L and non-potable flush toilets, recycling/digital showers, non-potable water used for cleaning, dishwashers and washing machines.
S4 – Technology and innovation	49	Very high levels of water efficiency. *Changes to micro-components include* automation and waterless fixtures/fitting e.g. 1.5 L toilets, recycling showers, smart taps, waterless/non-potable machines.
S5 – Regulation and compliance	73	Water service providers do not adapt to water scarcity despite increased public awareness. Regulators apply strict controls. *Changes to micro-components include* regulation pushes lower volume toilets and uptake of recycling/digital showers, regulation and water labelling delivers more efficient machines.

** NB. These figures include system losses that have been omitted from the household simulations*

The water savings described in these five scenarios have been quantified on an appliance-specific basis by Artesia (2018). As the microcomponents have been described for each scenario, it was possible to re-calibrate SIMDEUM® to generate household discharge patterns emerging from each case. SIMDEUM® can be calibrated for this purpose by adapting the frequency of use or discharge volume of an appliance, or by defining new appliance characteristics (e.g. waterless washing machines or non-potable flush toilets). Figure 3.2-1 displays the input and output flow from a household in each scenario. Bathroom and kitchen taps were lumped as one micro-component in Artesia (2018) and thus have been divided between the kitchen and bathroom in the ratio of the baseline scenario, which is based on typical UK household data (Energy Saving Trust, 2013). The 'system losses' defined by Artesia (2018) have been omitted from the household simulation as these are not dependant on the population and do not enter the sewer. The discharge profile for each appliance may differ from the demand profile if the flow is diverted from entering the sewer, i.e. in cases of external water use or greywater reuse. Greywater reuse was utilised in scenarios S3 and S4, collection in these scenarios comes only from the shower or bath and is provided for toilet flushing, dishwasher or washing machine use, as defined in the scenario description. The discharge to the sewer in these scenarios was calculated by first calibrating the appliances for potable water to reflect the water input (for appliance using non-potable water, the intake was set to zero). Once calibrated with the water input the households were simulated again including the non-potable appliances, this produced the total demand of both potable and non-potable appliances. Conducting a mass balance over the water within the household revealed the quantity of shower/bath water required for the GWR and the water discharge from these appliances updated accordingly. Scenario 3 requires more non-potable water than what is produced by the bath and shower and therefore an additional 2.4 L cap^{-1} d^{-1} would be required, perhaps provided by means of rainwater harvesting.

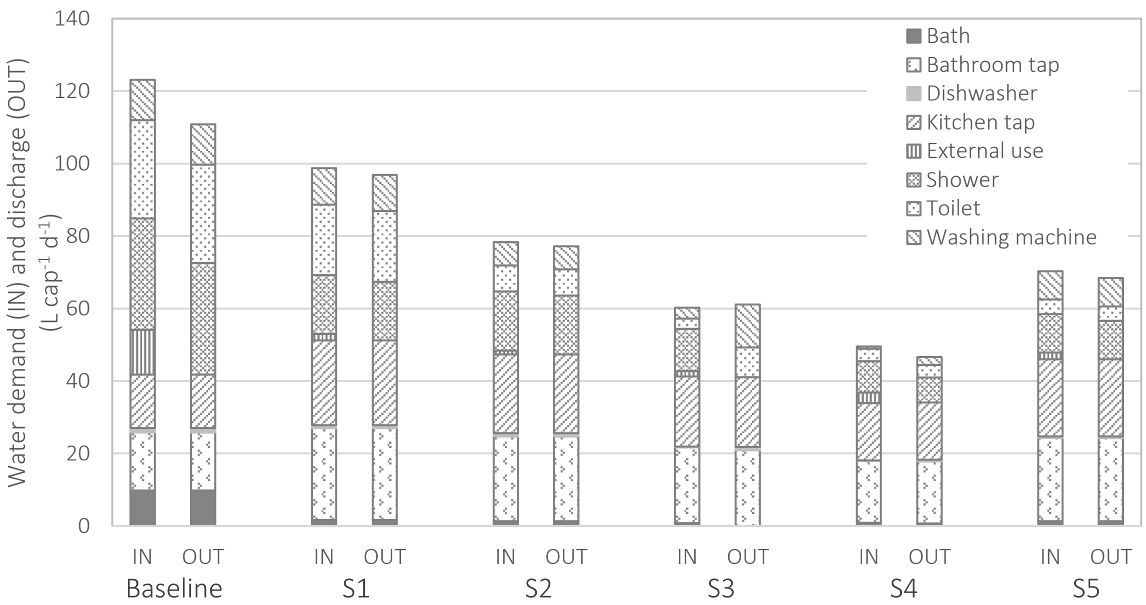

Figure 3.2-1. Outline of appliance demand and discharge for each of the future scenarios (Appliance inputs from Artesia (2018))

3.2.5 Results and discussion

3.2.5.1 Hydraulic modelling for future water use scenarios

Figure 3.2-2 shows how the presented water use scenarios affect daily flow from the modelled catchment. It can be seen that flow is not reduced equally throughout the day which highlights the importance of using an appliance-specific probabilistic model for this analysis. By visual inspection of Figure 3.2-2, it can be seen that the most dramatic effect on flow comes during the morning peak and into the evening. This suggests that as we tend towards more water saving appliances there will be less variability in diurnal wastewater flow patterns. This flatter daily profile could lead to smaller pipe diameters and pipe capacity being utilised more evenly throughout the day. Pipes have traditionally been sized to accommodate the system peaks which results in them flowing close to empty for a large part of the day. The drop in the morning peak is due to the decreasing volume of the toilet flush and increased efficiency of showers. Quantified changes to the peak and average flow, velocity and water depth have been displayed for each scenario in Table 3.2-3.

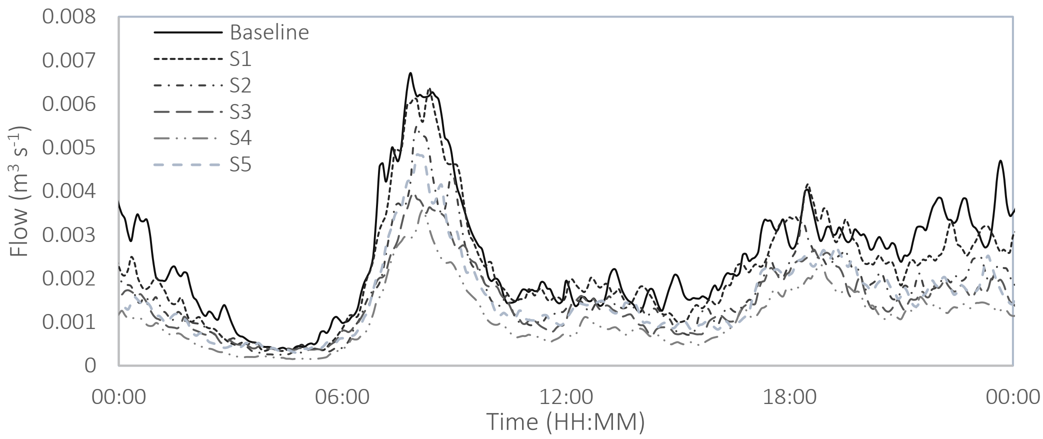

Figure 3.2-2. Variation in weekday wastewater flow patterns at the catchment outfall resulting from future water use scenarios. Note: this stochastic output demonstrates a snapshot from one possible run scenario.

It can be seen in Table 3.2-3 that decreases in water use between 15-60% could amount to a 1-48% drop in the morning peak. These peak impact estimates show to be more conservative than those presented by Penn et al. (2012) who conducted a similar analysis using a deterministic model. The two scenarios presented in that work assessed a water use drop of 26% and 41% from a baseline of 138 L cap^{-1} d^{-1} and found that the morning peak would be reduced by up to 53% and 58% respectively. As this study was conducted using a continuous discharge pattern, identical for each household, it misses the impact of the impulse discharges into the system. This is thought to be the reason that the stochastic model reveals a lesser impact on flow, it allows assessment of appliance changes without assuming a global effect over the entire flow pattern. This highlights a strength of the presented model in that every modelled household is unique which allows a variety of appliances to be modelled simultaneously, i.e. some households may install a 1 L flush toilet but others may keep their old 9 L flush toilet and this can now be simulated without assuming that an appliance change effects the entire flow pattern equally.

Table 3.2-3 also shows that, the flow velocity in the outfall pipe at peak flow drops below the standard self-cleaning velocity of 0.75 m s^{-1} for scenarios 2-5 which could indicate the potential for blockage problems in the network and could warrant further investigation. However, the shallowing of the morning peak could take the pressure off existing infrastructure if future populations are set to increase or new developments are planned, reducing the need for costly expansions and replacements. It is important to note that in these scenarios network design and population statistics remained constant. Average flow reduces mostly in line with the average demand whilst velocity and depth reduce by almost half as much as the flow.

Table 3.2-3. Outlining the effect that various water use scenarios have on peak and average sewer flow, velocity and depth at the catchment outfall. This is amounting from the simulation of one week. Each effect has been compared to the validated baseline model.

		Baseline	S1	S2	S3	S4	S5
	Average demand (L cap^{-1} d^{-1})	123	105	86	62	49	73
	% change from baseline		-15%	-30%	-50%	-60%	-41%
Peak							
	Flow (L s^{-1})	6.80	6.75	5.50	4.39	3.57	4.83
	% change from baseline		-1%	-19%	-35%	-48%	-29%
	Velocity (m s^{-1})	0.80	0.80	0.74	0.68	0.63	0.70
	% change from baseline		-0.3%	-8%	-15%	-22%	-12%
	Depth (cm)	5.10	5.10	4.70	4.30	4.00	4.50
	% change from baseline		0%	-8%	-16%	-22%	-12%
Average							
	Flow (L s^{-1})	2.39	2.12	1.65	1.40	1.10	1.54
	% change from baseline		-12%	-31%	-41%	-54%	-35%
	Velocity (m s^{-1})	0.51	0.49	0.44	0.42	0.37	0.43
	% change from baseline		-5%	-14%	-18%	-28%	-16%
	Depth (cm)	3.39	3.25	2.99	2.86	2.61	2.93
	% change from baseline		-4%	-12%	-16%	-23%	-14%

3.2.5.2 Water quality modelling for future water use scenarios

Linking the flow pattern with the typical water quality produced by a certain appliance made it possible to assess how wastewater concentrations vary throughout the day and under various water use scenarios. Figure 3.2-3 shows an example pollutant discharge profile for one household from SIMDEUM WW®. It shows a range of high and low concentration discharges produced throughout the day and reflects that often events of high water use are typically low concentration and low water use events more concentrated.

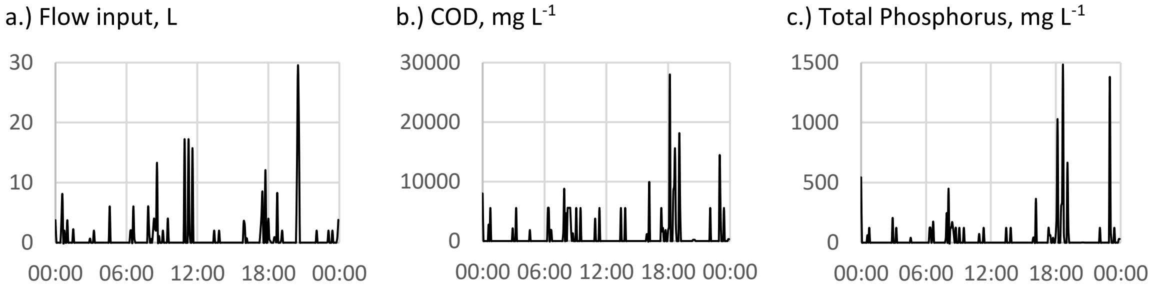

Figure 3.2-3. Example diurnal pollutant discharges from a household generated using SIMDEUM WW®

Table 3.2-4 quantifies how average wastewater concentration varied between future scenarios. Pollutant profiles have been shown for COD, TKN, TPH and wastewater temperature as these are parameters that are most important to make an assessment for resource recovery. It can be seen that COD concentration was predicted to increase 2-3 times the equivalent reduction in water flow. Nitrogen and phosphorus typically increase by a lesser amount than COD for the equivalent reduction in use. These rates of concentration increase are broadly comparable with those found by Penn et al. (2012) but are slightly higher as that study considered a decreasing in pollutant load through GW treatment and garden irrigation. Increased nutrient concentration comes at the sacrifice of wastewater temperature in the cases that utilise GWR as shower/bath as shower/bath water is no longer discharged to the sewer.

Table 3.2-4. Quantifying the impact that future water use scenarios have on wastewater concentration at the catchment outfall. Each concentration change has been given in comparison to the baseline scenario.

	Baseline	S1	S2	S3	S4	S5
Average demand (L cap^{-1} d^{-1})	123	105	86	62	49	73
% change from baseline		-15%	-30%	-50%	-60%	-41%
<u>Average</u>						
COD (mg L^{-1})	1601	2484	2519	3145	4485	2653
%change from baseline		+55%	+57%	+96%	+180%	+66%
TKN (mg L^{-1})	119	196	196	198	258	141
%change from baseline		+65%	+65%	+66%	+116%	+19%
TPH (mg L^{-1})	64	83	85	118	197	99
%change from baseline		+30%	+33%	+83%	+206%	+53%
Temperature (°C)	28.7	27.6	27.7	24.5	25.7	26.9
%change from baseline		-4%	-3%	-15%	-10%	-6%

The concentration of nutrients typically increases in line with water use reduction, with the exception of nitrogen. In the case of nitrogen, scenarios 1-3 produce similar concentrations, scenario 3 would be expected to produce higher concentration nitrogen than the S1 and S2 however this lower concentration result is thought to be due to the total removal of shower and bath discharge. Pollutants from these appliances are diverted to high water use appliances such as the washing machine, dishwasher and toilet but in a much-reduced load due to greywater pre-treatment. Table 3.2-4 presents the averaged results from a week-long simulation. These results were subjected to the removal of outliers (1% of results at either extremity), this is in order to present the most typical average concentration from each scenario. Scenario 5 produces the lowest average nitrogen concentration, which is thought to be due to most of the flow reductions emerging from reduced usage frequency rather than appliance upgrade. Low flush volume toilets and increased dishwasher efficiency are the largest water use reductions in this scenario which are not substantial enough to account for more than 1% of the time hence the reduced average once outliers were removed.

Figure 3.2-4 shows the variation in COD, TKN and TPH concentrations as well as wastewater temperature at the catchment outfall. It can be seen from these plots that the wastewater concentration is reasonably high when compared to typical influent concentrations at wastewater treatment plants (Tchobanoglous and Burton, 1991) but in comparison to upstream simulations in the work of Penn et al. (2013), the obtained values for similar flows are comparable. These values represent what is possible from a small separated sewer network where pollutants have not yet been greatly diluted by infiltration or rainwater. Groundwater infiltration has not been modelled in this study so these values serve as a potential to what could be achieved in upgraded networks. This is also a fairly small catchment where wastewater is relatively fresh and free of the dilution that occurs in longer sewer networks. The concentrations agree with values published by Henze (1997) when exploring the potential concentration effects of water conservation in households, where, based on water consumption of 80 L cap^{-1} d^{-1}, wastewater concentrations of 2750 mg COD L^{-1}, 184 mg TKN L^{-1} and 35 mg TPH L^{-1} were reported. In comparison with the presented results of this study, phosphorus is the only parameter that was over-predicted, this is likely due to a difference in washing detergents used in the studies considered as this is the major input of TPH. The mass balance on total pollutants produced using SIMDEUM WW® also matches data found for the typical mass of pollutants produced per person (Henze et al., 2008; Tchobanoglous and Burton, 1991). Henze et al. (2008) published daily per capita load of 25-200 g COD, 2-15 g TKN and 1-3 g TPH, this study produced ranges of 173-228 g COD, 8-17 g TKN and 5-9 g TPH (based on 2.27 persons per household). Again it is seen that phosphorus was over-predicted. It is worth noting that quite some time has passed since the studies were conducted that inform the water quality components used in this study, in which water use habits and appliances have changed. For example, there has been recent changes in EU legislation to reduce phosphorus use in detergents (Regulation (EU) No. 259/2012) and a study conducted by Arildsen and Vezzaro (2019) reflected a decrease in wastewater phosphorus concentrations over recent years. It is therefore a recommendation from this study, that more recent data is collected on appliance-specific wastewater concentrations to better inform this work.

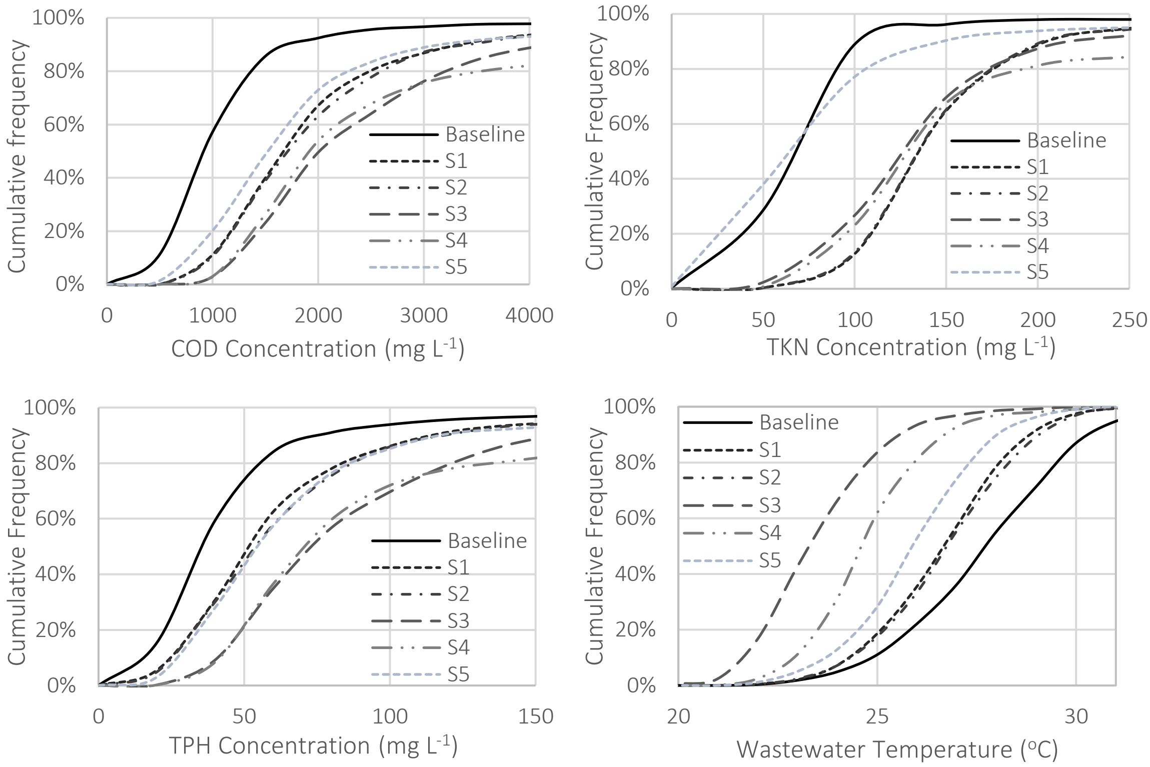

Figure 3.2-4. Variation in wastewater quality parameters (COD, TKN, TPH concentration and wastewater temperature) obtained with the stochastic water quality model at the catchment outfall.

A future development for this modelling approach would be to build stochastics into wastewater quality as well as discharge flow. SIMDEUM® is a stochastic model, but this approach utilises fixed concentrations per appliance. For example, the full and half flush toilet will contain different substances and concentration but is currently described by one average concentration per usage. In the case of the washing machine, the first discharge may have no washing powder and the second discharge all of it. This extension would require a larger set of appliance-based quality data than is presently available but would be a significant step forward in modelling accuracy.

3.2.6 Conclusions

This work demonstrates the use of a new stochastic sewer model to predict changes in flow and pollutant concentrations in the sewer resulting from water conservation. The hydraulic aspect of this model was developed, tested and validated in previous work. As the hydraulic model was deemed representative of the current system it was used to investigate the flow and concentration effects resulting from five future water use scenarios. Wastewater quality parameters were incorporated within this model by assigning average appliance pollutant load to the stochastic appliance based flow model. It was found that water saving appliances have the effect of flattening the diurnal wastewater discharge pattern, this could mean smaller pipe diameters and more stable pipe capacity throughout the day. In cases of population growth putting a strain on existing infrastructure water conservation could alleviate the risk of overflow. Scenario testing revealed that a 15-60% reduction in water use reflected a 1-48% drop in the morning peak. For the same range of water reduction, the effects on wastewater concentration were predicted to be 55-180% rise in COD, 19-116% rise in TKN and 30-206% rise in TPH. The next steps in this work will be to take measurements to validate the water quality prediction of the model and work on improving the calibration of wastewater quality parameters on an appliance-usage basis.

3.2.7 Acknowledgements

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Chapter 4

A stochastic model to predict flow, nutrients and temperature changes in a sewer under water conservation scenarios

This work was published in Water (MDPI) in April 2020.

Bailey, O., Zlatanovic, L., van der Hoek, J. P., Kapelan, Z., Blokker, E. J. M., Arnot, T. C., Hofman, J. A. M. H., 2020. *A stochastic model to predict flow, nutrients and temperature changes in a sewer under water conservation scenarios*, Water **12**(4): 1187. DOI: https://doi.org/10.3390/w12041187

This work was completed in collaboration with the New Urban Water Transport Systems (NUWTS) project based at Delft University of Technology (TU Delft)

4.1 Context

The previous chapter outlined the further development of the sewer model to incorporate wastewater quality. However, the values used for wastewater quality were collected from literature as typical discharge from household appliances. Some of these figures had large ranges and since they were reported, appliances and pollutants have changed (Arildsen and Vezzaro, 2019). There has been recent changes to EU legislation for example that banned the use of phosphorus in detergents (Regulation (EU) No. 259/2012). It was therefore necessary to gain a better understanding of wastewater quality today and how this changes over the day. It was decided to launch a data collection campaign in order to validate the wastewater quality aspect of the stochastic sewer model. Therefore, the aim of this work was to collect wastewater quality data for the validation of the wastewater quality model and to justify the use of SIMDEUM WW® as a household profile generator for flow and wastewater quality.

The work conducted in this chapter was undertaken during a research visit to Delft University of Technology (TU Delft). This visit provided a unique opportunity to collaborate with the New Urban Transport Systems (NUWTS) group and conduct testing of the methodology within a new case study. This collaboration aimed to create a comprehensive urban water model for observing effects of future water use scenarios on the entire water system (drinking water and wastewater). This wider project aims highlight a future vision for the urban water cycle and support investigations into optimal resource recovery within drinking and wastewater systems.

This chapter is submitted in an alternative format in line with Appendix 6A of the "Specifications for Higher Degree Theses and Portfolios" as required by the University of Bath.

The work completed in this paper was conducted by the author with the exception of the following:

- The network model (excluding household discretisation) was produced by WaterNet, the water utility of Amsterdam
- The wastewater sampling campaign was conducted by All Water Services (AWS, (www.aws-water.nl) and the sample analysis was conducted by Eurofins Omegam.

Statement of Authorship

This declaration concerns the article entitled:	
A stochastic model to predict flow, nutrients and temperature changes in a sewer under water conservation scenarios	
Publication status (tick one)	
Draft manuscript [ ] **Submitted** [ ] **In review** [ ] **Accepted** [ ] **Published** [x]	
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Copyright status (tick the appropriate statement)	
I hold the copyright for this material [ ]	Copyright is retained by the publisher, but I have been given permission to replicate the material here [x]
Candidate's contribution to the paper (provide details, and also indicate as a percentage)	The candidate contributed to / considerably contributed to / predominantly executed the… **Formulation of ideas:** Fully executed by candidate Supervision provided by Ljiljana Zlatanovic, Jan Peter van der Hoek, Zoran Kapelan, Jan Hofman. **Design of methodology:** Fully executed by candidate Supervision provided by Ljiljana Zlatanovic, Jan Peter van der Hoek, Zoran Kapelan, Jan Hofman. **Experimental work:** Fully executed by candidate with the exception of the following: -The network model (excluding household discretisation) was produced by WaterNet, the water utility of Amsterdam - The wastewater sampling campaign was conducted by All Water Services (AWS, (www.aws-water.nl) and the sample analysis was conducted by Eurofins Omegam. Supervision provided by Ljiljana Zlatanovic, Jan Peter van der Hoek, Zoran Kapelan, Jan Hofman. Software guidance provided by Mirjam Blokker. **Presentation of data in journal format:** Fully executed by candidate. Review and editing provided by Jan Hofman, Mirjam Blokker, Ljiljana Zlatanovic, Jan Peter van der Hoek, Zoran Kapelan and Tom Arnot.
Statement from Candidate	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature.
Signed	 **Date** 16/07/2020

4.2 Water (MDPI) paper

A stochastic model to predict flow, nutrient and temperature changes in a sewer under water conservation scenarios

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4.2.1 Abstract

Novel methods for saving water in homes are emerging to tackle issues of water scarcity. Reducing water use is likely to impact existing sewer systems but this impact is not currently well understood. This work describes a new flow and wastewater quality model developed to investigate this impact. The model uses SIMDEUM WW® to generate stochastic appliance-specific discharge profiles that include an appliance-specific wastewater quality profile. These discharge profiles were fed into InfoWorks® ICM to quantify the impacts within the sewer network. The model was validated by comparing the outputs obtained (flows and water quality) with the corresponding measured field data from a sewer system in Amsterdam serving 418 households. Wastewater concentrations of TSS, COD, TKN, TPH were sampled and wastewater temperature was measured on an hourly basis, over a one-week period. The results obtained showed that the InfoWorks® model predicted the mass flow of pollutants well (R-values 0.69, 0.72 and 0.75 for COD, TKN and TPH respectively) but, due to the current lack of a time-varying solids transport model within InfoWorks®, the prediction for wastewater concentration parameters was less reliable. Still, the model was deemed capable of analysing the effects of three different water conservation strategies (greywater reuse, rainwater harvesting and installation of water-saving appliances) on flow, nutrient concentrations, and temperature in sewer networks. Results show, through a 62% reduction in sewer flow, an increase

of COD, TKN and TPH concentrations by up to 111%, 84% and 75% respectively, offering more favourable conditions for nutrient recovery.

4.2.2 Keywords

Sewer Design; Stochastic Sewer Modelling; Wastewater Quality, Household Discharge; Reduced Water Consumption

4.2.3 Introduction

Contemporary water cycle infrastructure has typically been developed to promote public health and safety by supplying wholesome drinking water and by transporting wastewater and stormwater out of urban areas as quickly as possible. This has led to linear water use (take, use, throwaway) that is sub-optimal on grounds of sustainability. With growing environmental awareness, the idea of a circular economy has emerged, and a paradigm shift is required to close the water cycle and re-classify wastes as resources to recover and reuse. Resource recovery from wastewater is more effective at high concentrations. This can be achieved through dewatering processes at treatment plants (Bianchini et al. 2015, Diamantis et al. 2013, Mezohegyi et al. 2012) but another option is to limit wastewater dilution in the collection process (Verstraete and Vlaeminck 2011). Limiting wastewater dilution can be achieved by reducing domestic drinking water use, separation of storm/wastewater systems and preventing groundwater inflow by repairing/replacing broken pipes. This reduces nutrient loss from the cycle whilst reduced drinking water demand and wastewater transportation volume could save cost by reducing demands on existing infrastructure. Transporting more concentrated flow with a smaller pipe/equipment size requirement is also facilitated. Urban water cycles could enable resource recovery if considered from this new value proposition. This philosophy has prompted the development of a water cycle model to investigate the effects of future water use behaviours on the urban water system, and ultimately highlight how these systems could deliver enhanced resource recovery. This paper describes the development of a stochastic wastewater quality model and the comparison of this model to monitored field data. The sewer model forms part of a wider aim to develop an integrated water cycle model using a combination of SIMDEUM® and InfoWorks® WS/ICM packages. The integrated model will predict flow and wastewater quality changes in both drinking water and wastewater infrastructures, to evaluate the consequences of future water use scenarios.

Water demand and water quality models can be developed as deterministic or stochastic models. In a deterministic model, the results are fully based on pre-set parameter values and initial conditions. Stochastic models will include randomness and each time the model is used it will produce a different output. The advantage of deterministic models is the relative ease of use, whilst stochastic models will provide better insight in the system's dynamics. Because water use at the household level is extremely dynamic and follows random patterns, we have chosen to use a stochastic approach for this project as it gives a better reflection of reality.

A number of models have been developed to predict the impacts of various water conservation measures on the sewer system. These models have been largely deterministic (Parkinson et al. 2005, Penn et al. 2012, Penn et al. 2013) and have tested specific impacts of rainwater harvesting (RWH) and greywater reuse (GWR) on wastewater quality. Penn et al. (2013) reported pollutant concentration increases of 6-42% COD, 7-73% TSS, 9-57% NH_4-N and 7-52% PO_4-P for flow decreases of 8-41%. However, these deterministic approaches model domestic wastewater production as a continuous discharge based on averaged data, assuming an identical water use pattern for all residents. In reality, individual household wastewater profiles are a discontinuous series of discrete points, and hence a stochastic model is needed to model household discharges which are more representative of this reality. Penn et al. (2017) published a stochastic wastewater generator that does not require a great amount of input data, but which is based on empirical sampling, and assumes that the observed flow data (from 15 households) represents the flow of the target population. The flow generator was used as an input to a network model that assessed ability of flow to move gross solids (GS) in the sewer. GS movement was assessed through calculating critical flow required to move solids, but this does not link solids/pollutant generation to the discharges themselves. If we are to model water use changes that have not yet been observed, a model based on deterministic methods or empirical sampling is insufficient. There is therefore need for a stochastic sewer model that is independent of observed data for predicting impacts of changing water use. To our knowledge there is currently no sewer model that links unique appliance-discharge patterns to the specific water quality attributes produced by household appliances. Developing a model with this capability will offer a better understanding of how and when pollutants/nutrients build up in sewers, and how various water use changes could affect this in future.

This paper utilises a more complex stochastic generator than that developed by Penn et al. (2017). This tool, SIMDEUM® (Watershare 2016) , generates appliance-specific flow patterns based on probability parameters linked to appliance usage, household composition, and consumer water use behaviour (Blokker et al. 2010). Patterns produced by SIMDEUM® are specific to each appliance (e.g. toilet, sink, washing machine, etc.) which makes it possible to investigate explicit water use changes without assuming typical water usage patterns based on historical data. SIMDEUM WW® extends from SIMDEUM® to convert demand patterns into wastewater discharges, including thermal and nutrient loads (Pieterse-Quirijns et al. 2012). This conversion is achieved through correcting the flow rate or delaying the time of discharge e.g. toilets can take minutes to fill but seconds to discharge. Thermal and nutrient loads from each appliance are incorporated into the discharge profile by assigning typical (per use) load to each appliance.

Bailey et al. (2019) developed a stochastic flow model to assess the impact of water conservation on the sewer. This model utilised stochastic household discharge patterns (generated with SIMDEUM WW®) as input to a sewer network model based in InfoWorks® ICM. The flow model was validated using data from an English catchment, provided by Wessex Water (UK-based water utility). The flow model was extended to include wastewater pollutant concentrations by linking typical wastewater quality data to appliance-specific discharges within SIMDEUM WW® and utilising the InfoWorks® ICM wastewater quality model (Bailey et al. (2020). The flow/quality model was used to simulate and compare a series of future water use scenarios. The water quality aspect of this model, however, has not previously been compared to field data to assess its validity. This paper details a wastewater quality monitoring campaign conducted in a small housing estate in Amsterdam with that objective.

The paper is organised as follows: firstly we describe the model development and the methodology behind the wastewater quality monitoring campaign. Followed by the framing of six future water use scenarios that were tested using the model. Then, a description of the Amsterdam-based catchment used to analyse the model precedes the model predictions and a comparison of modelled parameters with the measured data. Finally, we make key conclusions.

4.2.4 Methodology

A model was developed to simulate the effects of future water use scenarios in sewers. The Infoworks® ICM (Sewer Edition; Innovyze Ltd, Oxfordshire) hydraulic and wastewater quality model was used to simulate the sewage system. This model was integrated with stochastic discharge patterns generated using SIMDEUM® and SIMDEUM WW® (Blokker 2011, Blokker et al. 2010). The MATLAB® codes behind SIMDEUM® were edited to make its outputs compatible with InfoWorks® ICM. Six future water use scenarios were framed and simulated using the validated model, allowing flow and concentration effects to be evaluated.

Infoworks® ICM Sewer Edition is an industry standard for 1-dimensional sewer network modelling. The software offers accurate analysis of hydraulics and water quality in sewer and stormwater networks. The model uses a network of nodes and conduits and solves the flow and mass balances for the network, based on water quantity and quality input, fed into the model via the nodes. The geometry of the network and the shape of the conduits is defined by geographical input and data from the real network.

4.2.4.1 Household discharge modelling

Hydraulic discharge model

The SIMDEUM® software tool was developed in the Netherlands for accurate water demand modelling. It can generate household water demand patterns based on statistical and probabilistic information about inhabitants and their appliance usage (Blokker et al. 2010). The SIMDEUM® pattern generator was calibrated for use in the studied catchment (Prinseneiland) which is described in Section 4.2.4.4, details of the studied catchment are shown in Section 4.2.5.

Wastewater quality loading

SIMDEUM WW® was used to link each wastewater discharge with an appliance-specific wastewater quality profile. SIMDEUM WW® originally included very little detail on pollutant discharges, having been used simply to demonstrate the possibility of nutrient discharge modelling (Blokker and Agudelo-Vera 2015, Pieterse-Quirijns et al. 2012). Therefore, a review of relevant literature (Blokker and Agudelo-Vera 2015, Butler et al. 1995, Parkinson et al. 2005, Parkinson 1999, Siegrist et al. 1976, Surendran 1998) was conducted to find appropriate input values for nutrient simulation. These input parameters describe pollutant mass per discharge for each household appliance (see Table 1), and the derivation of these parameters is described in Bailey et al. (2020). The nutrient discharge aspect of SIMDEUM WW® has never been validated. Through comparison of the wastewater quality model with measured data from this work, the phosphorus (TPH) parameters reported in literature were found to be too high. This is due to recent changes in EU legislation reducing phosphorus use in detergents (Regulation (EU) No. 259/2012). The phosphorus parameters were corrected to align with this legislation and are highlighted in bold in Table 1. The phosphorus associated with the kitchen tap was approximated in Comber et al. (2013) to be 0.03 grams person^{-1} day^{-1}, this enters the sewer through the disposal of food scraps. The other value shown in Table 4.2-1, i.e., 0.03 g use^{-1}, which depicts quality profile for each discharge, was found by calibration based on observed wastewater data and above assumed phosphorus value. The phosphorus from toilet use was updated in accordance with Comber et al. (2013), and assuming, on average, six toilet uses per person, per day.

Quality of non-potable water sources was quantified using data from Penn et al. (2012) (greywater) also Ward et al. (2010) and Farreny et al. (2011) (rainwater) - see supplementary information. This was combined with appliance pollutant quantities, shown in Table 4.2-1.

Table 4.2-1. Appliance-specific pollutant concentrations for improved SIMDEUM WW® (adapted from Bailey et al. (2020)). Bold values were defined in this work using observed wastewater data.

Appliance	Temp. (°C)	Sewage Quality (g use^{-1})				Ref.
		COD	TKN	TPH	TSS	
Bath	36	25.90	0.85	**0.00**	8.88	1
Shower	35	12.60	0.49	**0.00**	4.32	1
Bathroom tap	40	1.48	0.04	**0.00**	0.56	1
Kitchen tap	40	7.48	0.35	**0.03**	4.68	1,2
Dishwasher	35	30.00	1.35	**0.00**	13.20	1
Washing machine	[35,35,35,45]	65.25	0.68	**0.00**	17.10	1
- With GWR		*69.40*	*0.78*	**0.00**	*17.88*	4
- With RWH		*66.29*	*0.86*	**0.00**	*17.72*	5
Toilet	23	11.22	1.99	**0.22**	3.04	2,3
- With GWR		*11.48*	*2.00*	***0.22***	*3.09*	4
- With RWH		*11.28*	*2.00*	***0.22***	*3.08*	5

[1] Parkinson et al. (1999, 2005), [2] Comber et al. (2013), [3] Blokker & Agudelo-Vera (2015), [4] Derived from Penn et al. (2012) [5] Derived from Ward et al. (2010) and Farreny et al. (2011)

4.2.4.2 Stochastic sewer model

Wastewater flow and quality were simulated through a sewer network using InfoWorks® ICM (Sewer Edition; Innovyze Ltd, Oxfordshire). Stochastic household discharge patterns, described in Section 4.2.4.1, were imported into InfoWorks® ICM to produce time-varying domestic wastewater event. Each property has a unique flow and associated wastewater concentration profile as input to the sewer; discharges were input with one-minute intervals (maximum output resolution).

InfoWorks® ICM incorporates both hydraulic and wastewater quality modelling components. The hydraulic component was validated by Bailey et al. (2019) using measured flow, depth and velocity data. Saint-Venant equations govern hydraulics in InfoWorks® ICM. The wastewater quality model runs parallel to the hydraulic model, as described in Bailey et al. (2020), but was not validated. The concentration of dissolved pollutants and suspended sediment at every node in the sewer network is calculated for every time step using the InfoWorks® *network model.* The governing equation at a node is given by conservation of mass, Equation 4.2-1. Pollutant inflows arrive from incoming conduits and any external sources, in this case, wastewater events (household discharges). It is assumed that nodes are well-mixed and there is no deposition or accumulation.

$$\frac{dM_J}{dt} = \sum_i Q_i c_i + \frac{dM_{sJ}}{dt} - \sum_o Q_o c_o \tag{4.2-1}$$

Where:

M_J = mass of suspended sediment or dissolved pollutant in node J (kg)

Q_i = flow into node J from link i (m^3 s^{-1})

c_i = concentration in the flow into node J from link i (kg m^{-3})

M_{sJ} = additional mass entering node J from external sources (kg)

Q_o = flow from node J to link o (m^3 s^{-1})

c_o = concentration in the flow from node J to link o (kg m^{-3})

The InfoWorks® *conduit model* then calculates the concentration of dissolved pollutants and suspended sediment in each conduit. A conduit is a conceptual link of defined length between two nodes. One-dimensional flow is assumed in the conduit, as are well-mixed concentrations across each section of the conduit. Pollutants are assumed move through the conduit with the local mean flow velocity, and dispersion along the conduit is negligible. Wastewater determinants were all treated as dissolved pollutants because InfoWorks® ICM software fails to recognise time-varying suspended solid input. The authors have been advised that this shortfall will be corrected in a future software update. Therefore, wastewater determinants in the model are transported through advection, with no erosion, deposition, or accumulation of sediments. The advective mass flow between each element is shown in Equation (4.2-2).

$$F_a = F_m \times c_{upwind} \tag{4.2-2}$$

Where:

F_a = mass flow through the face due to advection (kg s^{-1})

F_m = volumetric flow through the face (m^3 s^{-1})

c_{upwind} = c_l if volumetric flow is from left to right element, c_r otherwise (kg m^{-3})

Where:

c_l = determinant concentration in left element (kg m^{-3})

c_r = determinant concentration in right element (kg m^{-3})

<u>Adjusting to allow for mixing in the sampling tank</u>

The sampling campaign, described in Section 4.2.4.3, generated data on wastewater in the pump feed tank rather than wastewater flowing in the sewer system (see Figure 4.2-1). As the sewage flows into the tank it mixes with the held-up water and thus the samples will reflect a dampened wastewater concentration compared to model predictions. The sewer model output was adjusted to allow for this mixing to allow comparison of model predictions with sampled concentration data.

Equation 3 is the derived expression for concentration in the tank (C_A), assuming the volume remains approximately constant (average volume of 1.6 m^3, midway between high and low levels). It also assumes that no reactions occur in the tank and the wastewater has a constant density. The tank concentration was plotted alongside measured data and modelled sewer concentration in Figure 4.2-11.

$$C_A(t) = (C_{A,in}(t) - C_{A,o})(1 - e^{-\frac{Q(t)}{V}t}) \quad (4.2\text{-}3)$$

Where:

C_A = Concentration of pollutant A in the tank (kg m^{-3})

$C_{A,in}$ = Concentration of pollutant A into the tank (kg m^{-3})

$C_{A,o}$ = Initial concentration of pollutant A (kg m^{-3})

Q = Flowrate into tank (m^3 s^{-1})

V = Tank volume (m^3)

t = Time (s)

4.2.4.3 Methodology for field testing

Data availability for validating the hydraulic discharge model

The Prinseneiland catchment (Figure 4.2-3) has three sources of hydraulic water network data. Two water mains supply drinking water to the island; a flow meter was present in each, providing live data recording of water demand. 58% of catchment households have a water meter recording specific water use, but this is mainly for billing purposes as data is summed over the period between physical meter readings. The final data source was provided by pump flow and tank level readings, recorded at the wastewater pumping station. Readings are recorded every 2-5 minutes dependant on changes recorded by the level controller. A variable speed pump switches on when the tank level reaches the programmed high level (above the inlet pipe) and off when the level reaches the programmed low level (above the pump). The volumetric flowrate through the pump was measured using an ECOFLUX electromagnetic flowmeter (www.krohne.com) (accuracy ± 0.5% of the measured value at velocities ≥ 0.4 m s^{-1} and ± 0.002 m s^{-1} if velocity is below 0.4 m s^{-1}). The tank level was measured using two VEGABAR 52 (www.vega.com) sensors, where the deviation is reported to be less than 0.075%. By performing a mass balance on the flow through the pump and the changing level in the tank (Equation 4.2-4), it was possible to convert these readings into a sewer flow profile (Equation 4.2-5).

$$V_{[\tau_n,\tau_{n+1}]} = PC_{(n)} \cdot \left(\tau_{(n+1)} - \tau_{(n)}\right) + \frac{A(LS_{n+1}-LS_n)_{S1}+A(LS_{n+1}-LS_n)_{S2}}{2} \quad (4.2\text{-}4)$$

$$Q_t = \frac{\sum_t^{n=0} V_{[\tau_n,\tau_{n+1}]}}{t} \quad (4.2\text{-}5)$$

Where:

$V_{[\tau_n,\tau_{n+1}]}$= Volume entering the tank between level sensor readings (m^3)

PC = Pumping capacity (m^3 s^{-1})

LS = Tank level (m)

A = Tank area (m^2)

$S1, S2$ = Level sensors

τ = Sample time (s)

Q_t = Wastewater flowrate into the tank (m^3 s^{-1})

t = Time (s)

Field testing of wastewater quality

At the end of August 2019, a wastewater quality campaign was carried out on Prinseneiland to collect data necessary for validating the wastewater quality component of the stochastic sewer model. The campaign was conducted continuously over 7 days, under dry weather conditions. Wastewater was sampled from the pump wet well at the end of the catchment, see Figure 4.2-3. All Water Services (www.aws-water.nl) carried out the fieldwork and the wastewater samples were analysed by Eurofins Omegam. A vacuum sampling device was used (photographs in the supplementary information). The sampling cabinet was placed within a portable toilet at street level to comply with space constraints and protect apparatus from damage. The sampling hose was secured at the sewer inlet to the wet well in such a way that the end of the hose was approximately 3 cm below the cut-off level of the pump. This ensured that the wastewater was as 'fresh' as possible when sampled from the tank, and thus most representative of the sewer flow. This method meant it was always possible to draw samples from the chamber, but during the night where wastewater flow is low, there is the possibility that stagnant wastewater is sampled. The sampling cabinet contained 24 1L bottles into which a 50 ml sub-sample was drawn every 3 minutes, i.e. 20 sub-samples per hour make up the 1L sample for that hour. The sample collection vessels were held at 1-5 °C. Sampling was carried out according to Dutch standard 'NEN 6600-1 (NL) Water - Sampling - Part 1: Waste water' from March 2009. Every 24 hours the completed samples were removed from the cabinet and decanted into three separate packages for separate analysis (see Table 4.2-2), and nitrogen and phosphorus were analysed from the same package. Samples were preserved on site according to Dutch standard 'NEN-EN-ISO 5667-3 (s) Water - Sampling - Part 3: Conservation and treatment of water samples' and were delivered daily to the analysis laboratory under cooling.

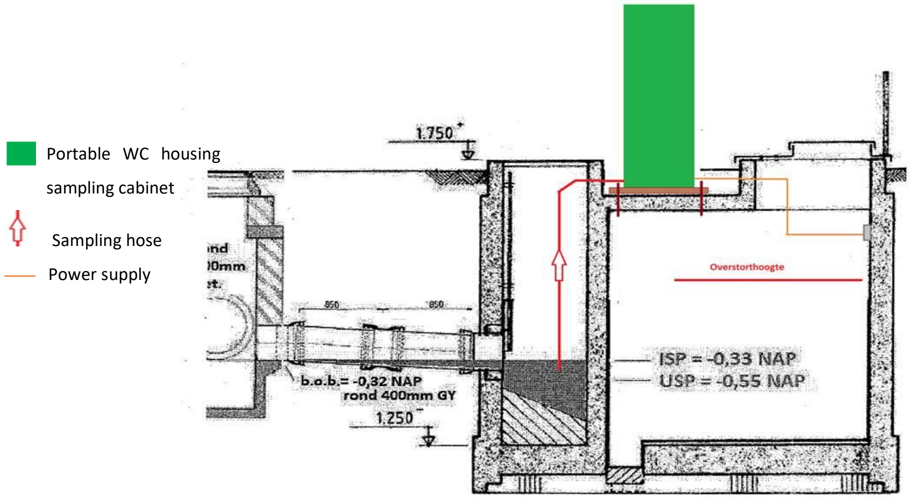


Figure 4.2-1. Wastewater sampling campaign equipment set up. Portable toilet housing the sampling cabinet that draws wastewater from the wet well of the pumping station in Prinseneiland. ISP is the level at which the pump switches on, USP is the level where the pump switches off. The tank area is 2 m^2.

Quality of sampling and analysis work

AWS are accredited according to the requirements as laid down in NEN-EN-ISO / IEC 17025: 2005 and Dutch Accreditation Council (RvA) regulations under number L599. Eurofins Omegam laboratory in Amsterdam (who carried out the sample analysis) is also accredited by RvA.

Wastewater quality parameters

The parameters analysed and the procedures followed by the laboratory are shown in Table 4.2-2.

Table 4.2-2. Water quality parameters analysed and specific methodology associated with each parameter

Parameter Sampled	Parameter description	Method (Eurofins Omegam)	Limit of determination (mg l^{-1})	Required sample volume (ml $sample^{-1}$)	Measurement uncertainty (+/-)
COD (mg l^{-1})	Chemical oxygen demand	Conforms to NEN 6633	5.00	100	15%
TKN (mg l^{-1})	Total Nitrogen-Kjeldahl	Conforms to NEN-ISO 5663	1.00	100	13%
TPH (mg l^{-1})	Total Phosphorous	Own method based on NEN-EN-ISO 15681_2	0.05	50	12%
TSS (mg l^{-1})	Total suspended solids	Conforms to NEN-EN 872 and NEN 6499	1.00	750	16%

4.2.4.4 Model validation

Procedure for model calibration

The SIMDEUM® model was calibrated by adjusting input variables describing household occupancy, home–presence, and specific details of household water use in the area. Households are characterised as either a single, dual, or family occupancy. Average occupancy and family size are also defined. The household data was derived from census data from the local government of the study area. Home presence data is culture and area-specific, and details typical times that people rise, go to work and go to bed. These data were obtained from the Netherlands Institute for Social Research (SCP) that conducts a five-year time-budget survey. Comparison of the model output with monitored catchment data showed a local deviation from the national survey data on wake up time, so this was adjusted on a case-specific basis. Household water use data is available from local water companies and should be input to the model to describe typical water use for each household appliance. The specific model adaptions made for the studied catchment are detailed in Section 4.2.5.2.

Procedure for model validation

Validation of the model was conducted by assessing the model performance over an average week. Dry weather flow data was selected at various points of the year (2 weeks from each season) to produce an average water use pattern of the catchment in order to compare with the model. The goodness of fit of model output was evaluated by computation of the Nash-Sutcliffe efficiency (NSE) and the root mean squared error (RMSE). The similarity of the flow patterns was evaluated with the correlation coefficient (R). The equations for NSE, RMSE and R are found below in Equations 4.2-6 to 4.2-8.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(x_{obs}-x_{sim})^2}{\sum_{i=1}^{n}(x_{obs}-\bar{x})^2} \tag{4.2-6}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(x_{obs}-x_{sim})^2} \tag{4.2-7}$$

$$R\,(X,Y) = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2\sum(y-\bar{y})^2}} \tag{4.2-8}$$

Where:

x_{obs} = Observed parameter

x_{sim} = Simulated parameter

$\bar{x}, \bar{y}$ = Sample mean of parameters x, y

4.2.4.5 Impact assessment for water conservation technologies

The development and validation of the sewer model allow it to be used to predict the effect of future scenarios. Table 4.2-3 describes the future scenarios that were developed for testing in the Prinseneiland catchment. These scenarios were based on total area reform (100% implementation). Water use scenarios include 'Eco', which involves an upgrade of household appliances (such as 1 L flush toilets and water-saving showers) and 'GWR'/'RWH', which utilise greywater or rainwater feed for toilet flushing and washing machines. Greywater and rainwater feed quality data are found in the supplementary material. Each scenario has been presented using future population statistics supplied by the Municipality of Amsterdam (Gemeente Amsterdam), as outlined in Table 4.2-4. The '(a)' scenarios are the maximum bound for occupation in the catchment, and the '(b)' scenarios explore the effect of a continued rise in single occupancy households, thus provides a minimum occupancy bound.

Table 4.2-3. Future scenario description

Scenario	Demand (L cap^{-1} d^{-1})	Description
1 – Baseline	112	Present-day scenario – validated hydraulic model
2a – Eco, max. occupancy	42	Water-saving appliances such as 1 L flush toilets and water-saving showers (as presented by Agudelo and Blokker (2014))
2b – Eco, min. occupancy	44	
3a – GWR, max. occupancy	67	Greywater reuse utilised for toilet flushing and washing machines
3b - GWR, min. occupancy	68	
4a – RWH, max. occupancy	67	Rainwater harvesting utilised for toilet flushing and washing machines
4b - RWH, min. occupancy	68	

***** a.) Amsterdam projected population statistics, b.) Reduction in average occupancy to 1.1

Table 4.2-4. Population statistics for present and future scenarios (based data and projections obtained from Gemeente Amsterdam)

	Single	Dual	Family	Family size	Occupancy
Baseline	58%	23%	19%	3.4	1.7
(a) Max.	55%	21%	24%	3.5	1.8
(b) Min.	91%	4%	5%	3.1	1.1

SIMDEUM® generates household discharge patterns based on the specific usage and discharge characteristics of household appliances. Figure 4.2-2 shows how these household micro-components vary between the scenarios. Differences in drinking water demand and discharge occur through the use of non-potable water sources (not included in water demand) or outdoor use (does not enter the sewer). In the case of greywater reuse and rainwater harvesting, household appliances were held at baseline water consumption. Water was only redirected to appliances, i.e. no internal mass balance for water movement was incorporated into the model. It is assumed that there will always be sufficient water in a storage tank to allow these appliance discharges.

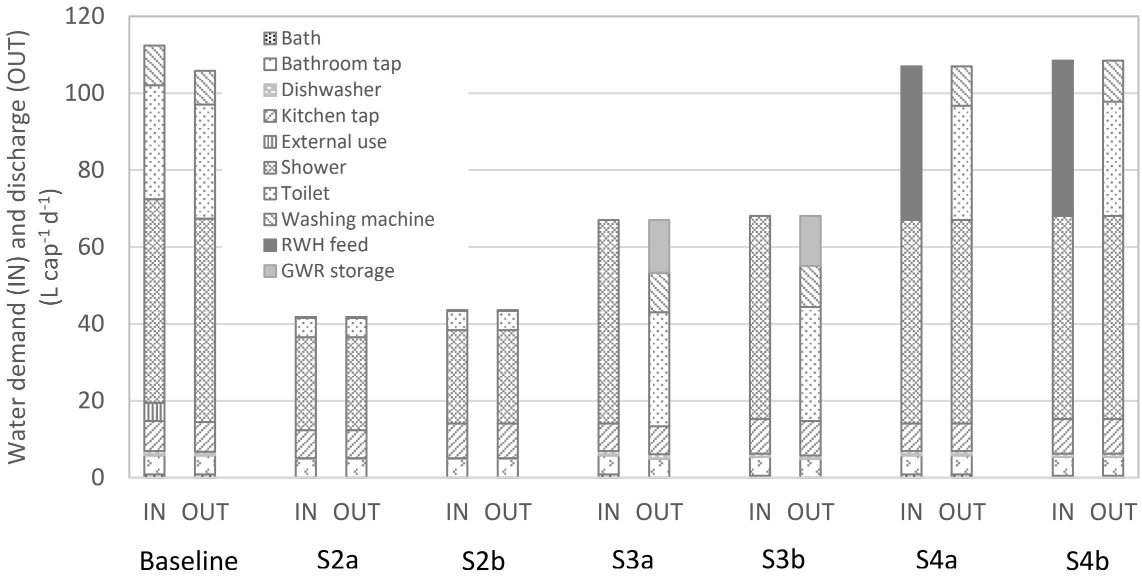


Figure 4.2-2. Outline of appliance demand and discharge for each of the future scenarios

4.2.5 Catchment used for model analysis

4.2.5.1 Description of the modelled catchment

Prinseneiland is a small housing estate located in Amsterdam, which is the capital and most populous municipality of the Netherlands. A map of Prinseneiland is found in Figure 4.2-3. There are 418 domestic households and 55 other premises (offices, ateliers, storage buildings) located in the housing estate.

The sewer system is a looped and combined network (i.e. stormwater and wastewater). Concrete sewer pipes, measuring 684 m (400-600 mm diameter and 1:1961 to 1:133 slope, the average slope was 1:615), lead to a pumping station where wastewater is pumped away from the housing estate for treatment. Flow and level monitors at the pumping station provide data for model validation every 2-5 minutes.

30 second time steps were used in calculations and simulations were conducted for 5 days. Results were typically analysed using 5-minute intervals but to facilitate comparison with the measured data (hourly intervals), the results time step was set to one-hour in these cases. Wastewater quality modelling parameters remained as the default with the exception of the temperature model parameters in which the heat transfer coefficient was 4×10^{-5} m s^{-1}, and the equilibrium water temperature was 23 ^{o}C, to align with the warm weather at the time of sampling.

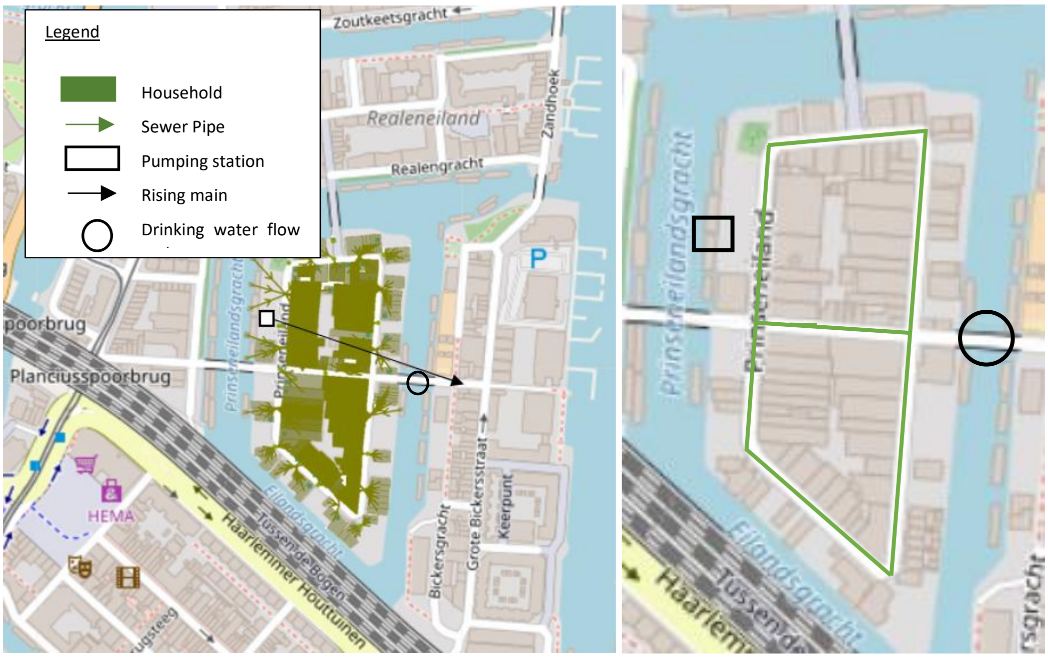
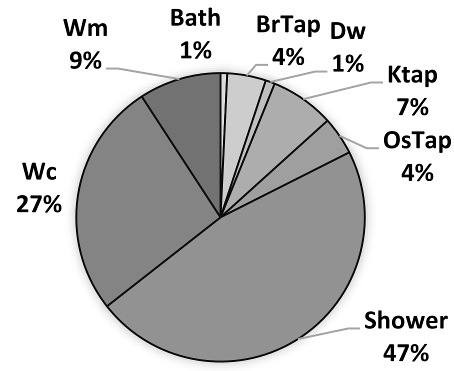


Figure 4.2-3. Map of modelled catchment – Prinseneiland, NL (WaterNet)

4.2.5.2 Model calibration details

The SIMDEUM® model was calibrated by changing input variables describing household occupancy, home–presence data and specific details of household water use in the area. The average household size in Prinseneiland is 1.7 people household^{-1}, where single, dual occupancy and family households are divided 58%, 23% and 19% respectively, see Table 4.2-4. This information was put into SIMDEUM® along with the data shown in Figure 4.2-4, which details the typical distribution of water use between household appliances (micro-components) on Prinseneiland. The split of water use between appliances was determined by applying a scale factor to the micro-component statistics for the whole of Amsterdam (Waternet 2019), as in Figure 4.2-4. Water and wastewater flow into and away from the island was monitored by the local water company, Waternet. The model output was compared with measured demand data from the island, and it was found that inhabitants seemed to rise an hour later than the Dutch average. The home presence schedules were therefore updated to give an average wake up time of 8 am (9 am for stay-at-home adults and seniors).



	Average water use ($L\ cap^{-1}\ day^{-1}$)	
Appliance	Amsterdam	Prinseneiland
Bath	1.0	0.8
Bathroom tap (BrTap)	5.8	4.9
Dishwasher (Dw)	1.4	1.2
Kitchen Tap (Ktap)	9.6	8.1
Outside tap (OsTap)	5.7	4.8
Shower	62.7	52.9
Toilet (Wc)	35.3	29.7
Washing machine (Wm)	12.3	10.3
TOTAL DAILY USAGE	**133.8**	**112.7**

Figure 4.2-4. Appliance-specific water use in Amsterdam, Netherlands (Waternet, 2019) and the derived appliance usage of Prinseneiland assuming the Amsterdam average micro-component trend

4.2.6 Results and discussion

4.2.6.1 Calibration and validation of the stochastic sewer flow model

Figure 4.2-5 shows the drinking water flow measured on entrance to the modelled catchment, demonstrating about a one hour delay between clean water entering the catchment and the sewer flow leaving the catchment. This is due to a combination of time in flow and hold up time of water used in household appliances before discharge. Figure 4.2-5 also shows that in the early hours of the morning this delay extends to almost two hours, which is likely due to the longer hold-up derived from increased use of dishwashers and washing machines. The water balance between drinking water and wastewater data in Prinseneiland revealed an average excess of 1.3 $m^3\ day^{-1}$ in the wastewater. This excess is likely due to infiltration to the sewer and runoff from the street, and represents approximately 2% of the dry-weather flow. This external inflow to the system could also explain some of the difference between drinking water and wastewater flows, particularly at night when flow is low.

Once SIMDEUM® had been calibrated as described in Section 4.2.4.4, the model represented the sewer system described in Section 4.2.5 reasonably well. Comparison of the model output with the sewer flow data can be seen in Figure 4.2-6 along with the model evaluation statistics (correlation coefficient, Nash-Sutcliff coefficient and the root mean squared efficiency, RMSE).

The model under-predicts the sewer flow during working hours, this is due to the assumption that the housing estate is purely domestic. There is an average discrepancy of 10 m^3 between the hours of 10:00 and 18:00, which can be explained by the metered usage of the business premises. 9% of the registered properties on Prinseneiland are business addresses and these vary in function from warehouses to offices. These businesses were not modelled as they are not easy to describe well, and this study primarily investigates the impacts of varying water use on domestic wastewater.

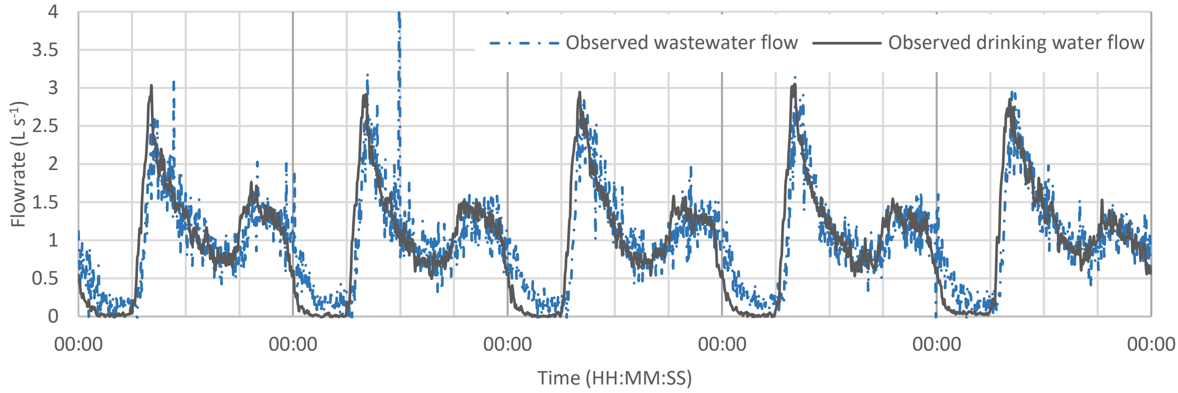
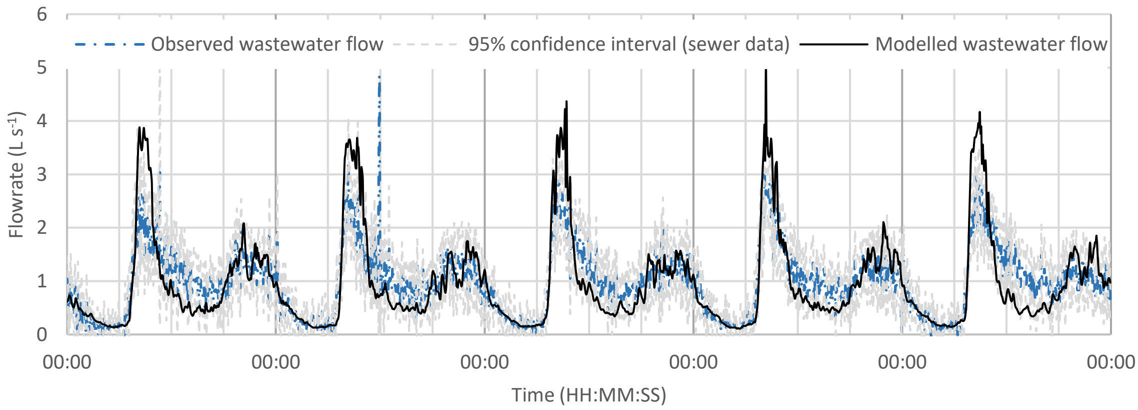


Figure 4.2-5. Comparison of the mean drinking water and wastewater flow in the studied catchment



	Modelled wastewater flow	*Averaged day*
Correlation Coefficient, R	0.806	0.832
Nash-Sutcliff Efficiency, NSE	0.481	0.639
RMSE ($L\ s^{-1}$)	0.453	0.472

Figure 4.2-6. Performance of stochastic sewer model when compared to measured sewer flow data. Note: the stochastic model output demonstrates a snapshot from one possible run scenario.

4.2.6.2 Sampling wastewater for quality analysis

To confirm that the wastewater quality model provides a good representation of real life, a week-long wastewater sampling campaign was carried out, described in Section 4.2.4.4. The sampling campaign began on a Thursday at 11 am and ran through until the following Thursday at 11 am. These results have been reordered to represent a Monday-Friday profile for ease of analysis – but it should be noted that the Thursday and Friday measurements were taken the week before the Monday – Wednesday measurements. The weekends have not been modelled due to the limited capacity of SIMDEUM® to describe weekend water use. Weekend water use is less strongly linked to a daily routine and SIMDEUM® has yet to be developed to incorporate this difference. The results of the sampling campaign are shown in Figure 4.2-7 to Figure 4.2-9. Figure 4.2-7 shows how the measured wastewater flow over the sampling week compared to the measured wastewater flow used to validate the hydraulic model, see Section 4.2.6.1. There was heavy rainfall from 20:35 until 21:05 on the Tuesday evening of the sampling campaign; this explains the flow peak shown in Figure 4.2-7 (indicated by an arrow) and its deviation from the calibration flow. Figure 4.2-8 and Figure 4.2-9 show the hourly measurements of wastewater concentration that were taken for total suspended solids, TSS, chemical oxygen demand, COD, total Kjeldahl nitrogen, TKN, and total phosphorus, TPH.

There was a good correlation between TSS and COD (R=0.82) and a reasonable correlation between TKN and TPH (R=0.55) but the correlation with suspended solids is weak (R=0.38 for TKN and R=0.20 for TPH). This indicates that the bulk of the COD is combined within the suspended solids but the TKN and TPH are present in a more dilute form. It is also notable that there is a reasonable correlation between the flowrate and the concentration of TSS and COD (R=0.78 and R=0.73 respectively). This seems to indicate that higher pollutant concentrations are produced at peak flow, but it is more likely that accumulated solids are washed through the system during high flow. This could be a consequence of sampling the wastewater downstream, where the highest concentration of COD/suspended solids occurs in the morning peak flow and the evening peak flow, but this is not necessarily the case upstream. This is discussed further in Section 4.2.6.3. TKN concentration also peaks with the morning surge in flow but then drops early afternoon, before steadily increasing throughout the evening until the next morning. TPH follows a very similar pattern to TKN but has a second evening peak in concentration. This is likely due to phosphorus sources now being restricted for the toilet and kitchen sink discharges, whereas the nitrogen is discharged more often.

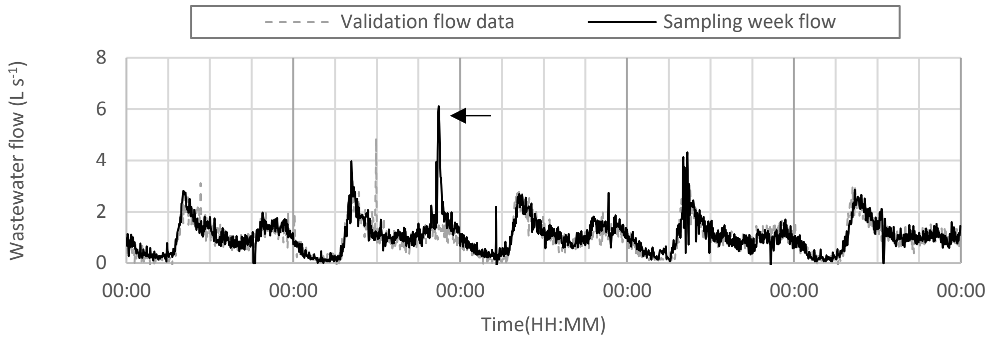


Figure 4.2-7. Wastewater flow over sampling week compared to flow data used for model validation

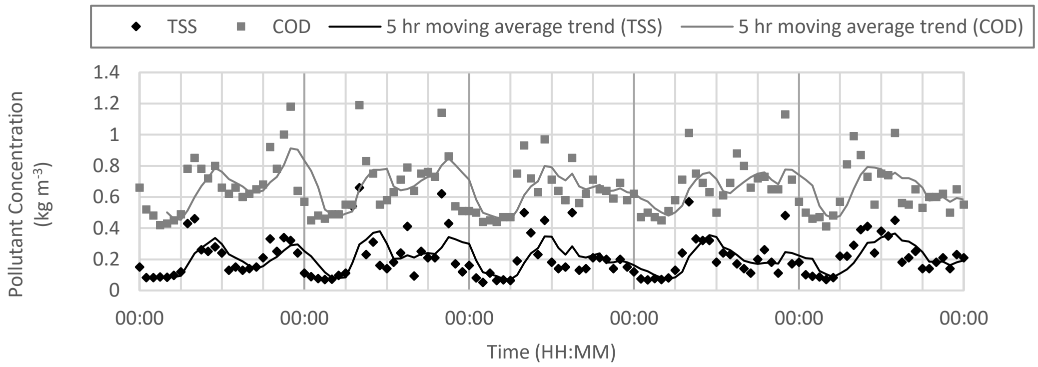


Figure 4.2-8. Hourly concentration of suspended solids and COD in wastewater over sampling week

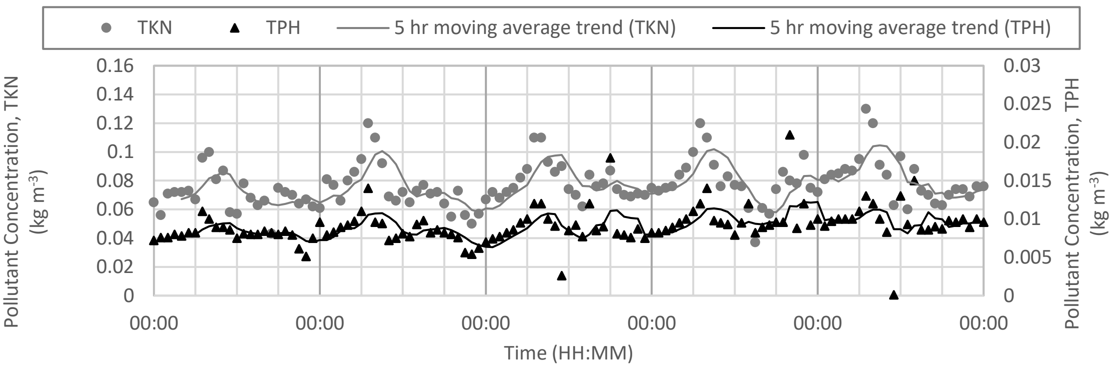


Figure 4.2-9. Hourly concentration of TKN and TPH in wastewater over sampling week

4.2.6.3 Model comparison with sewer quality data

Figure 4.2-10 shows a comparison of the modelled mass flow compared to the observed data (calculated as the product of the measured concentration and the measured wastewater flowrate). The shaded areas represent the sampling error associated with each parameter, highlighted in Table 4.2-2. As indicated in Section 4.2.6.2, there was heavy rainfall from 20:35 to 21:05 on the Tuesday evening of the sampling campaign, and this is reflected in the concentration peak on the second evening of the plots in Figure 4.2-10 (indicated by an arrow). Apart from this, the model represents the observed mass flow reasonably well, as the timing and magnitude of the mass flow profiles are in alignment with the measured values. The predicted mass flow overnight is, on average, higher than the observed mass flow, and the observed morning peak is higher than predicted. This confirms the hypothesis, in Section 4.2.6.2, that these flow peaks likely include accumulation of solids rather than higher concentration discharges from households. This build-up of suspended solids has not been accounted for in this version of the model as time-varying solid generation is not available in InfoWorks® (see Section 4.2.4.2).

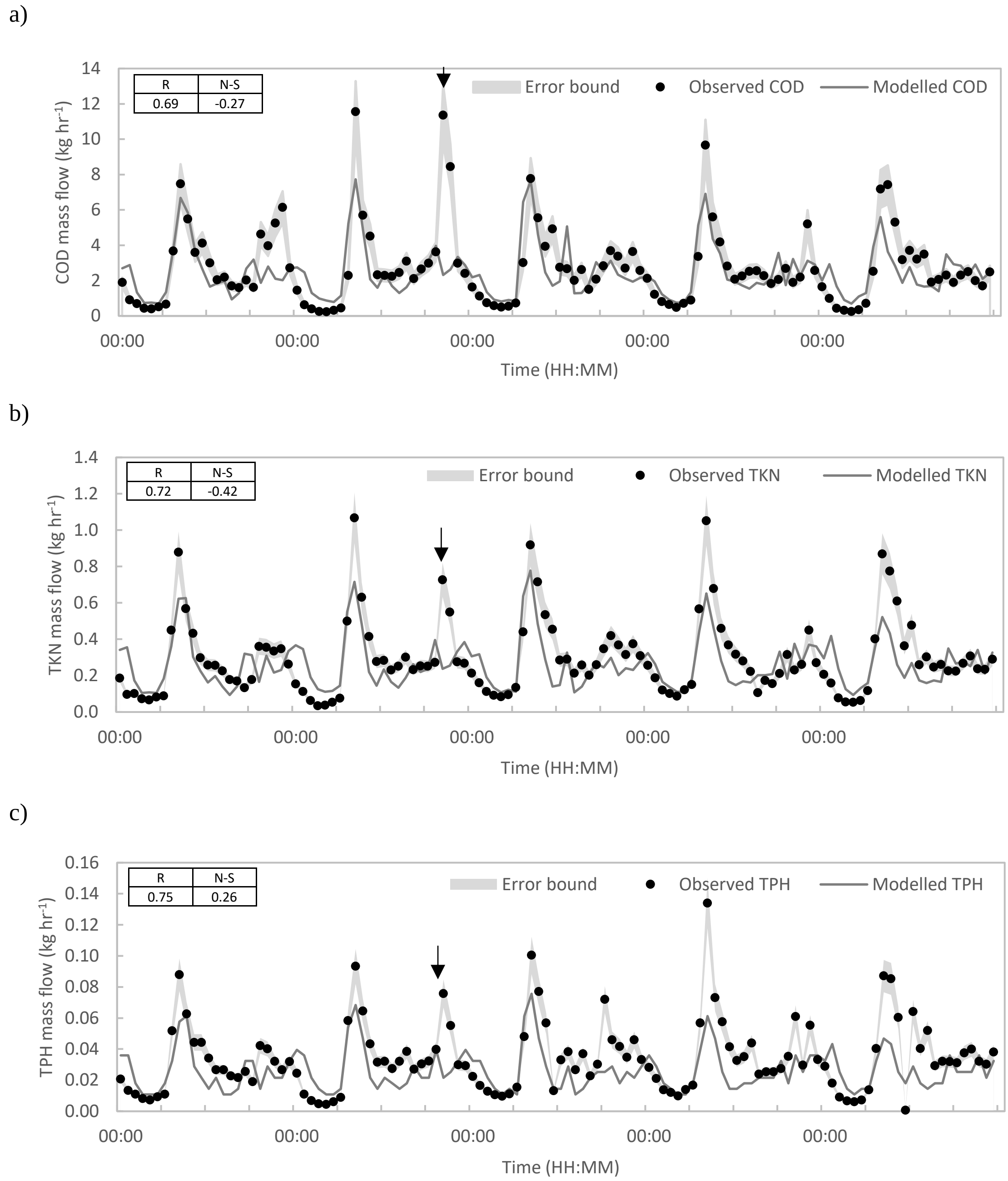


Figure 4.2-10. Mass flow of COD (a), TKN (b) and TPH (c) predicted by the model compared to the mass calculated from measured concentration and measured flow rate at the wastewater pumping station. The correlation coefficient (CC) and Nash-Sutcliff coefficient (N-S) are given for each plot. Note: the stochastic model output demonstrates a snapshot from one possible run scenario.

Figure 4.2-11 shows the comparison of the predicted and measured nutrient concentration. The modelled tank concentrations were calculated according to Equation 4.2-3. This also supports the conclusion that the discrepancy between the modelled wastewater concentration and the observed is due to the lack of differential solids transport modelling in the network. The model predicts concentration to be highest during the night as most water use at night is from toilets, but this cannot be confirmed by the measured data. Following the design of the sampling campaign, the high concentration wastewater produced at night would only be accounted for during the first few 3-minute sub-samples of the peak flow the following morning. The subsequent sub-samples are likely to be diluted substantially, leading to a morning peak in a lower concentration than the more concentrated night flows. SIMDEUM WW® appears to be performing well as a wastewater generator, but as the solids transport has not been adequately modelled within the sewer system (InfoWorks® ICM), the concentration cannot be aligned with the measured data. The modelled TKN and TPH follow the measured concentration data better than the COD, this is likely due to their lower correlation with suspended solids, and hence, dilute modelling is more appropriate here.

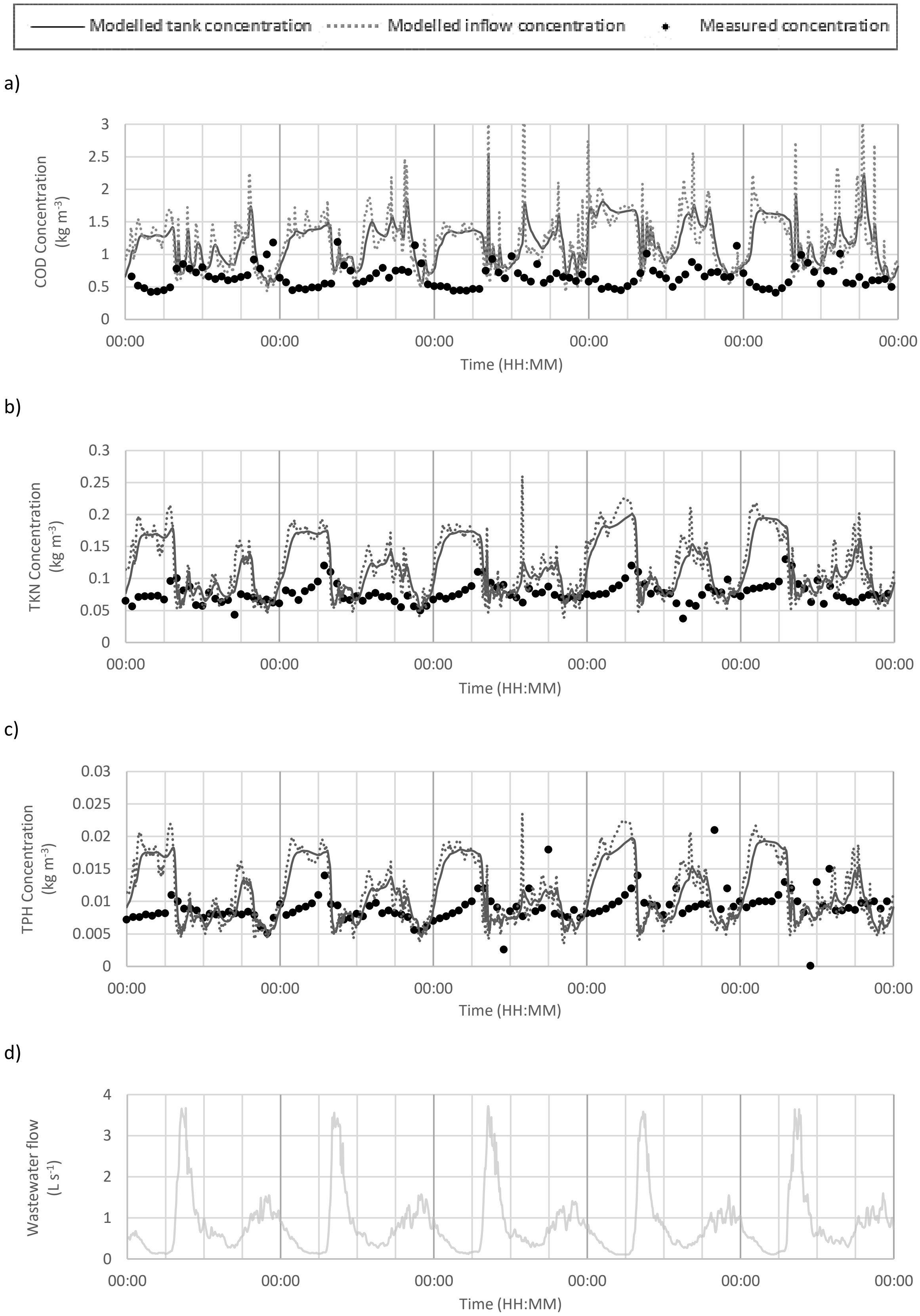


Figure 4.2-11. Modelled COD (a), TKN (b) and TPH (c) concentration in comparison with the measured concentration and wastewater flow (d). Note: the stochastic model output demonstrates a snapshot from one possible run scenario.

4.2.6.4 Variability of the model

To address the variability of the stochastic model, each weekday was evaluated on factors of flow and nutrient mass – see Figure 4.2-12, where each day is compared to the first simulated day. The sample point for comparison was the final pipe of the network, before the pumping station. The stochastic model results are relatively consistent as the gradient of the line of best fit, m, for each day is close to 1. Correlation between Day 1 of the simulation and the subsequent days is very high for flowrate but the correlation is less strong for the nutrient mass flow. COD showed the smallest variability followed by TKN and then TPH. This is thought to be due to TKN and TPH being linked more strongly to appliances that follow a less strict daily usage pattern e.g. kitchen taps, dishwashers and washing machines. Whereas the toilet and shower use (more strongly linked to COD generation) happen at similar times of day. Elias-Maxil (2015) assessed the variability in SIMDEUM® with over 200 simulations and concluded that the pattern generator reaches a steady state after 75 simulations, i.e. the variability approaches zero. As the studied catchment includes 418 households, this confirms that the variability at the outfall is low.

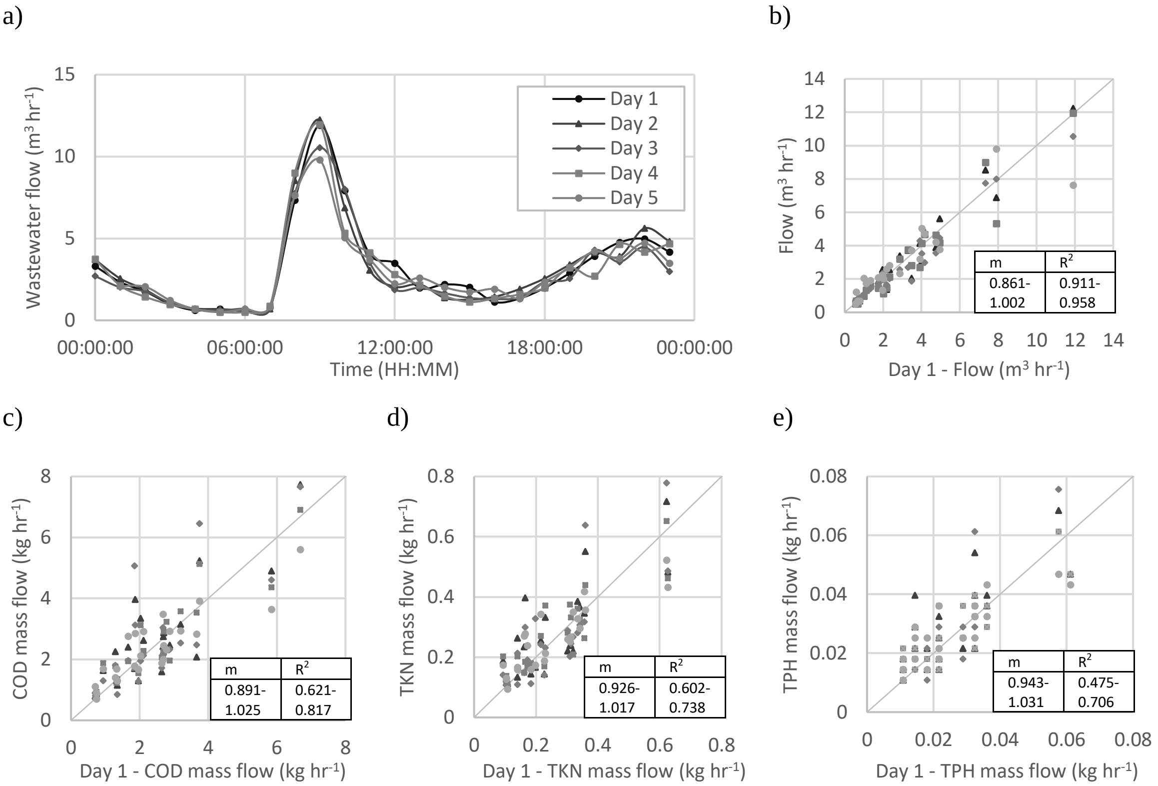


Figure 4.2-12. a) Variation in stochastic modelled flow over 5 days, b) Flow variation over 5 days compared to Day 1, c) COD mass flow variation over 5 days compared to Day 1, d) TKN mass flow variation over 5 days compared to Day 1, e) TPH mass flow variation over 5 days compared to Day 1

4.2.6.5 Future scenario testing

Six future scenarios (Section 4.2.4.5) were tested using the stochastic flow and wastewater quality model to observe the effects of different water conservation technologies on flow and wastewater concentration. Increased wastewater concentration can offer benefits for resource recovery, whilst reducing household water use is beneficial for water security and sustainability reasons.

Figure 4.2-13 shows the results from this simulation, analysed over a 5-day period (Monday-Friday). It can be seen in Figure 4.2-13a, that the effect of Eco (2a/2b) and GWR (3a/3b) scenarios is the dramatic reduction in the morning peak. The sewer system experiences a much narrower range of flowrates in these scenarios, which warrants smaller pipe diameters. Penn et al. (2014) stated that for a 1 - 6 mm diameter solid, the critical shear is 0.867 - 1.42 Pa, respectively, so without reducing pipe diameters, these water use scenarios may struggle to transport larger solids (see Figure 4.2-13b).

Figure 4.2-13(c-f) shows the consequence on wastewater quality parameters, and there is little impact of population changes between the scenarios (a and b scenarios). RWH produces a very similar situation to the baseline as it is simply replacing potable sources with a non-potable alternative. The impact of this scenario is better addressed by evaluating the impact on the drinking water system, as it will likely increase water residence time in the distribution network, which may compromise water quality. The Eco scenario produces the highest concentration of wastewater, although the range of concentrations is similar to the baseline/RWH scenarios. GWR produces wastewater at concentrations between the other two scenarios but in a much narrower range. This scenario could, therefore, be preferable for resource recovery as there is a narrower operating range for treatment units. However, GWR is the poorest performing water use scenario in terms of wastewater temperature, as shower and bath water do not directly enter the sewer, hence sewer temperature reduces. This model has been demonstrated as a useful tool for analysis of various resource recovery options for future urban water planning.

Bailey et al. (2020) concluded that this model over-predicts phosphorus concentrations, but with the results from the sampling campaign, and the changes made in the estimated wastewater composition due to the removal of phosphorus in detergents (Section 4.2.4.1), the model now predicts in line with reality. Daily pollutant load produced per capita in these scenarios ranged from 86-122 g COD, 8-12 g TKN and 0.8-1.2 g TPH – these values align with independently published values (Arildsen and Vezzaro 2019, Comber et al. 2013, Henze et al. 2008, Tchobanoglous and Burton 1991).

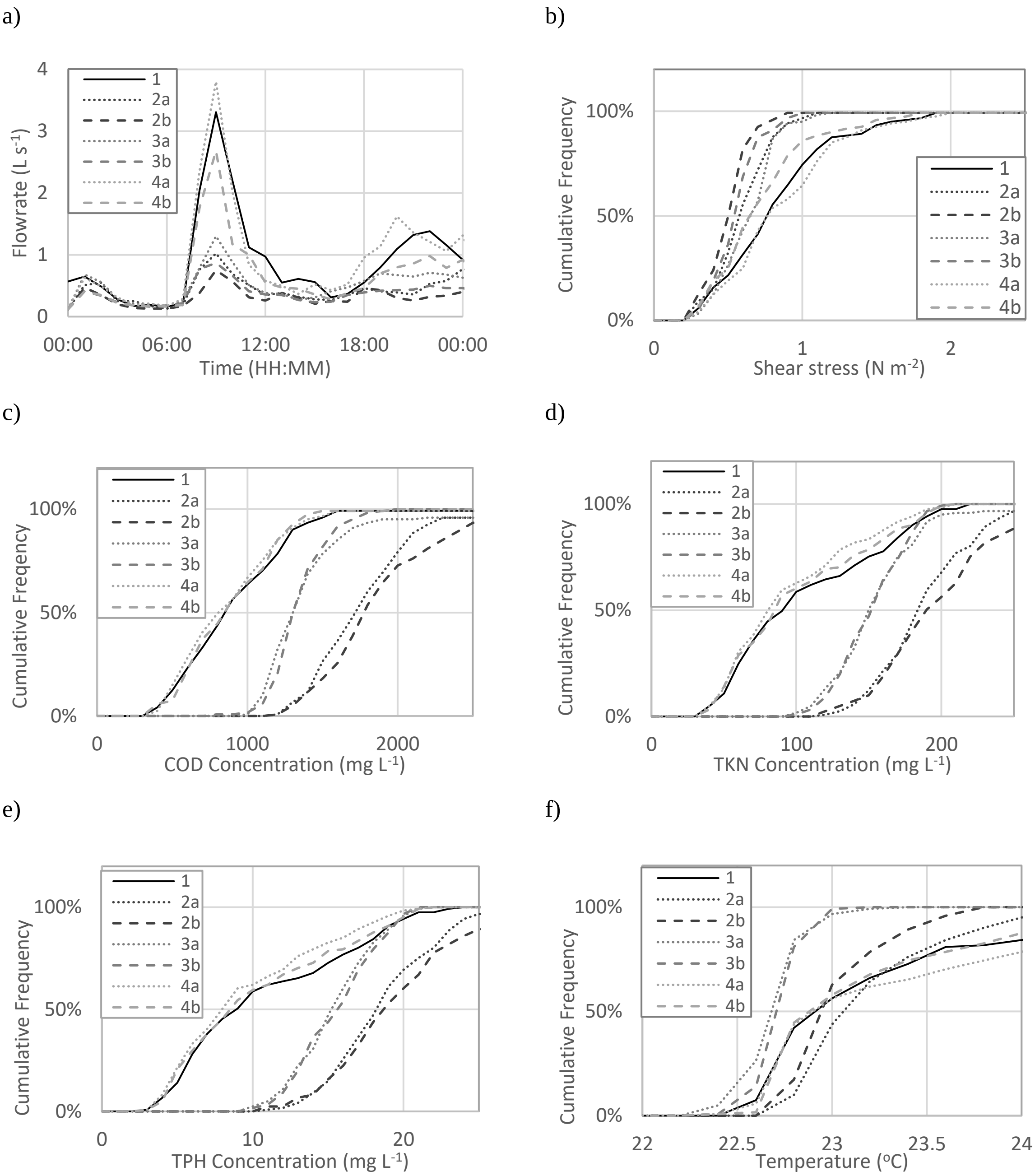


Figure 4.2-13. a) Effect of scenarios on the flowrate at the catchment outfall, b) Cumulative frequency of shear stress achieved at the catchment outfall over 5 days, c, d, e) Cumulative frequency of COD, TKN and TPH concentration in wastewater at the catchment outfall over 5 day (respectively), f) Cumulative frequency of wastewater temperature at the catchment outfall over 5 days. Note: the stochastic model output demonstrates a snapshot from one possible run scenario.

4.2.7 Conclusions

A new stochastic wastewater flow and quality model has been developed to address the impacts of water use changes on wastewater flow concentration. The hydraulic model was tested and validated in previous work. This paper presents the validation of the wastewater quality model using measured data. The model was used to investigate the impact of three water-saving strategies (greywater recycling, rainwater harvesting and installation of smart water appliances) on water quantity and quality in the sewer network.

The results obtained lead to the following key findings:

1. Stochastic sewer model wastewater quality validation

The predicted mass flows of COD, TKN and TPH compared well with the corresponding observed data values. The same, however, cannot be said for the COD, TKN and TPH concentrations. These concentrations were treated as dilute pollutants as InfoWorks® does not currently incorporate differential solids transport, leading to the misalignment of the predicted and measured concentration data. High concentration flows are produced by the stochastic generator during the night but only washed through the system in the morning. As the concentrations were measured at a downstream point in the network, there was a lag time in transporting suspended solids which was not accounted for in the network model.

2. Implications for three water-saving strategies on the quantity and quality of flow in the receiving sewer network

It was found that wastewater flow can be reduced by up to 62% with concentrations of COD, TKN and TPH increasing by up to 111%, 84% and 75% respectively with the installation of water-saving appliances. In addition, it was found that the use of water-saving appliances and greywater recycling dramatically reduced the peak flows, whereas rainwater harvesting produced similar flow and concentration results in the baseline case. The greywater recycling case produced the most consistent wastewater concentrations and the lowest wastewater temperature.

3. Proposals for future work

This will involve incorporation of the time-varying component for suspended solids entry to the sewer system, and differential solids transport in the sewer. This advancement will be combined with a drinking water simulation to create a comprehensive urban water model for observing effects of future water use scenarios on the entire system. This project will ultimately highlight a future vision for the urban water cycle and support recommendations for optimal resource recovery within drinking and wastewater systems.

4.2.8 Acknowledgements

This study was conducted as part of the Water Informatics Science and Engineering (WISE) Centre for Doctoral Training (CDT), funded by the UK Engineering and Physical Sciences Research Council, Grant No. EP/L016214/1. Olivia Bailey is supported by a research studentship from this CDT.

Funding was also obtained from the Topsector Water & Maritime TKI Watertechnology Program of the Dutch Ministry of Economic Affairs and Climate Change (No. 2016TUD003, project New Urban Water Transport Systems), water utility Waternet, drinking water companies Brabant Water, Limburg and Evides, water authority De Dommel, Amsterdam Institute for Advanced Metropolitan

Solutions and Royal Haskoning DHV Consultancy. The authors also thank WaterNet for providing expertise, data, and access to the sewer networks for field tests.

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4.2.10 Supplementary information

4.2.10.1 Additional information from the wastewater sampling campaign

Figure 4.2-14 shows photographs taken of the sampling equipment and set up described in Section 4.2.4.3.

a.) b.) *c.)*

Figure 4.2-14. Photographs of wastewater sampling installation on Prinseneiland. From left to right, a.) Automatic sampling cabinet with 24 sample bottles, b.) Portable toilet that housed the sampling cabinet with sampling hose leading through the manhole cover to wet well below, c.) View of sampling location once the installation of the sampler was completed.

4.2.10.2 Raw data from the wastewater sampling campaign

Figure 4.2-15 and Figure 4.2-16 show the complete concentration data set collected in chronological order starting at 11 am on 22/08/2019 (Thursday) and ending at 11 am on 29/08/2019 (Thursday).

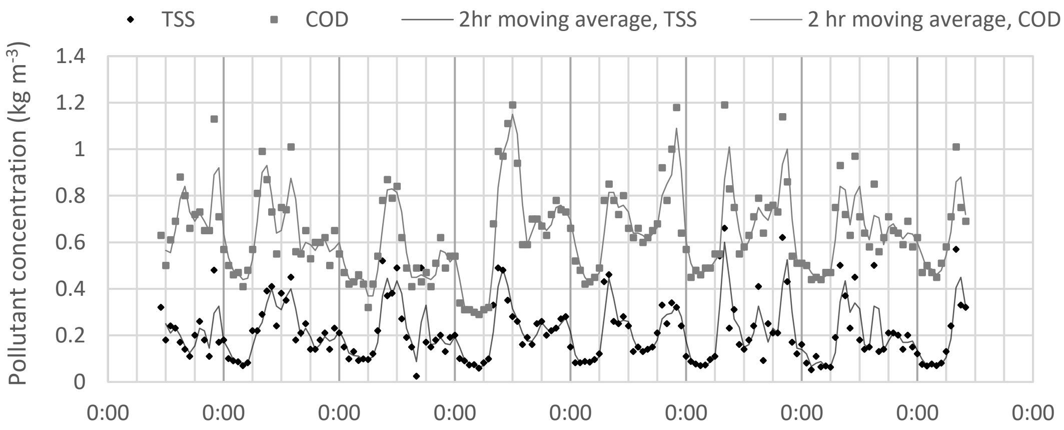

Figure 4.2-15. Complete COD and TSS concentration data set obtained from wastewater quality campaign

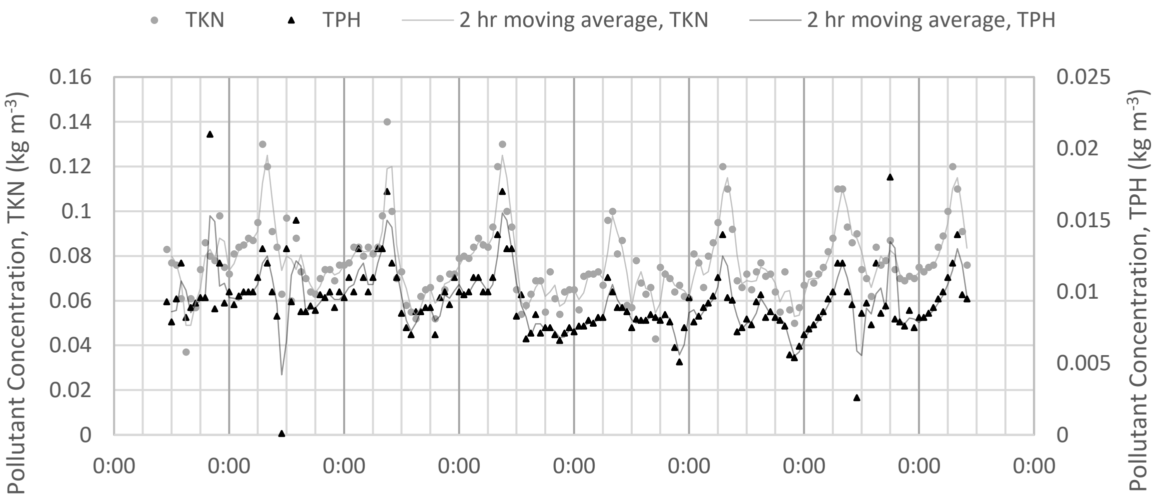

Figure 4.2-16. Complete TKN and TPH concentration data set obtained from wastewater quality campaign

4.2.10.3 Monitoring wastewater temperature

Methodology for wastewater temperature sampling

The temperature of the wastewater stream entering the pumping station was recorded every minute. The temperature sensor was of the Minilog type with accuracy ± 0.25% (www.endress.com). This is a battery-powered meter that was placed in the wet well and secured to the manhole cover. The temperature reading was checked daily using a calibrated field temperature meter. The temperature readings taken by AWS were confirmed by installation of an additional temperature sensor, Cera-Diver (www.vanessen.com), that recorded the temperature every 5 minutes over a two-week period. This diver had a typical measurement accuracy of ± 0.1 ^oC.

Results of wastewater temperature monitoring and modelling attempts

Figure 4.2-17 shows wastewater temperature over the sampling week (AWS) and the additional week monitored with the confirmation analysis, via the Cera-Divers.

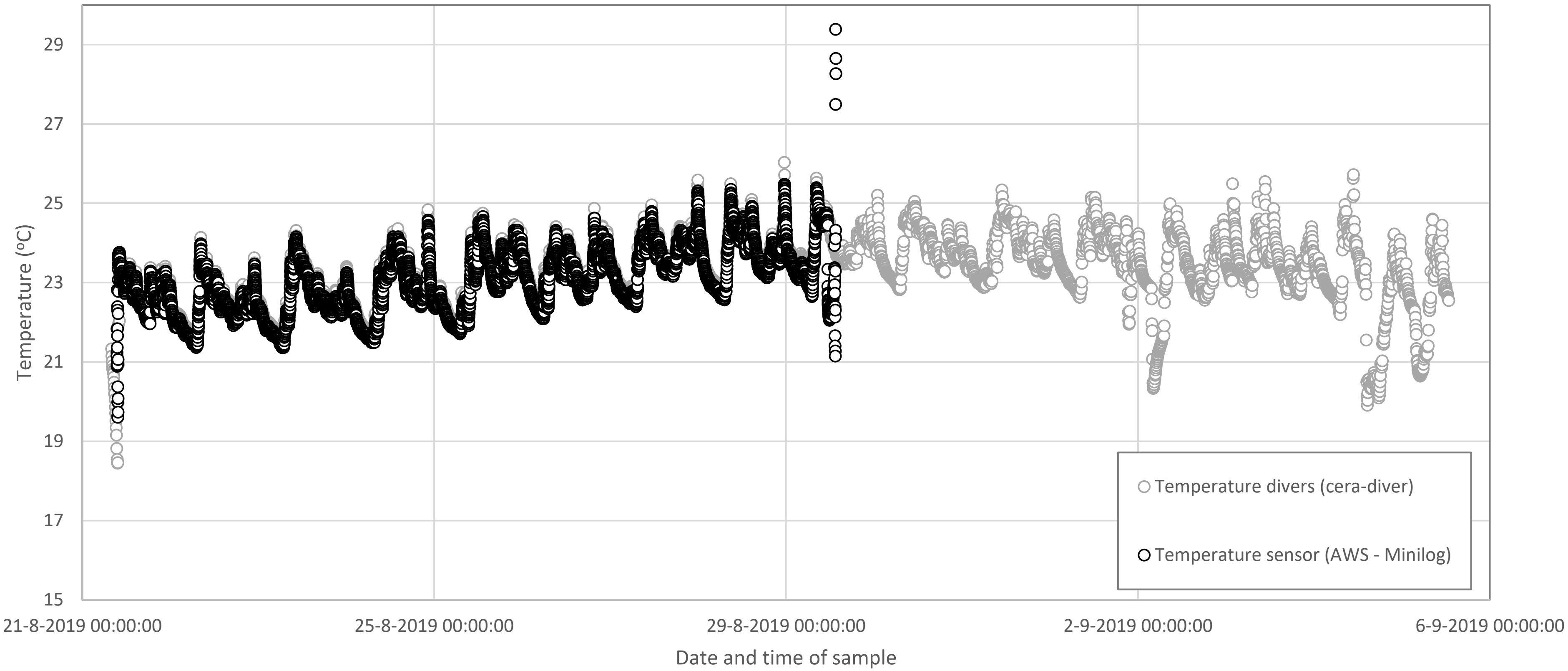

Figure 4.2-17. Wastewater temperature data collected at the entrance to the wet well at the end of the studied catchment

Figure 4.2-18 shows the predicted temperature compared with the daily-averaged measured data. The latter is the average temperature for each of the 5-minute intervals over the two-week measurement period. Temperature modelling within InfoWorks® ICM is very basic and can only be calibrated by two parameters: a single heat transfer coefficient at the water surface, and the equilibrium temperature (or air temperature). There was, therefore limited ability to calibrate the temperature model. The heat transfer coefficient was set to 4×10^{-5} m s^{-1}, and the equilibrium water temperature was set to 23 °C to align with the warm weather at the time of sampling. The model predicted a temperature profile in the appropriate range but the temperature modelling capabilities of InfoWorks® ICM are not as detailed as with other hydraulic software. A better model for temperature based modelling is the model implemented by Elias-Maxil (2017) using SOBEK®.

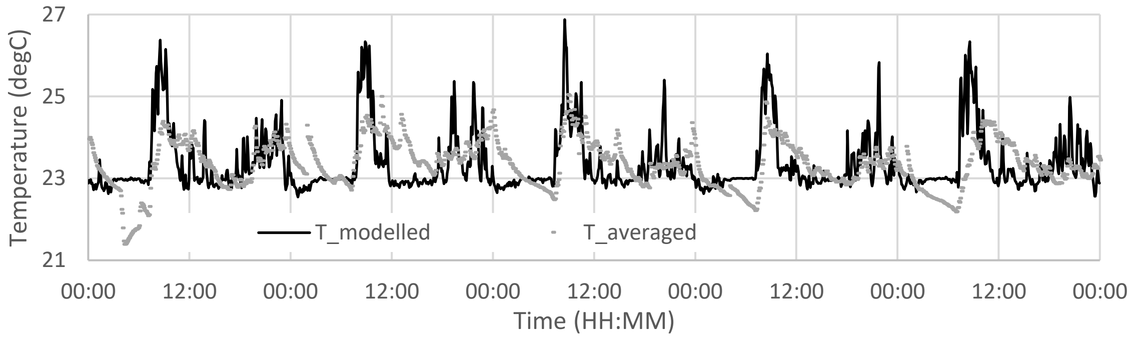

Figure 4.2-18. Predicted wastewater temperature compared with the measured and two-week averaged temperature

4.2.10.4 Non-potable feed water composition

The greywater composition profile used here was derived from Penn et al (2012). The rainwater pollutant concentration was taken from Ward et al. (2010) and Farreny et al. (2011). The greywater and rainwater feed compositions were originally described in terms of concentration, so these data were translated into mass discharge per appliance use. To do this, the average water use (per capita) for each appliance and the average number of uses per day (from Penn et al (2012)) were considered, together with the concentration data listed in Table 4.2-5. The toilet and washing machine were considered to use 37.7 L cap^{-1} day^{-1} and 16.6 L cap^{-1} day^{-1}, and they were assumed to be used 5.9 and 0.16 times per day, respectively.

Table 4.2-5. Greywater and Rainwater feed composition utilised in this work (Greywater derived from Penn et al (2012), rainwater derived from Ward et al. (2010) and Farreny et al. (2011))

Pollutant	GW effluent concentration (mg L^{-1})	Greywater feed per appliance (g use^{-1})		Rainwater feed per appliance (g use^{-1})	
		Toilet	Washing Machine	Toilet	Washing Machine
COD	40.0	0.26	4.15	0.06	1.04
BOD	1.8	0.01	0.19	0.02	0.31
TSS	7.5	0.05	0.78	0.04	0.62
TKN	1.0	0.01	0.10	0.01	0.18
NH3	0.1	0.00	0.01	0.00	0.05
TPH	2.0	0.01	0.21	0.00	0.00

4.2.11 References for supplementary information

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Chapter 5

Implications of water conservation on sewer network design

5.1 Introduction

This penultimate chapter of the thesis aims to reflect on the model produced and explore the wider impact of the model for the water industry. It aims to address how the work presented in this thesis could aid future sewer design and how it might help improve existing systems. It is inevitable that into the future we will continue to become more environmentally conscious, live in a more sustainable way and follow principles of circular economy. However, there is a real challenge of how these circular possibilities can be realised in the water cycle and how to transition to sustainable urban water management practices. In the UK alone we have 418,082 km of sewer system (Combined Services Ltd. 2016), of which some sections are over a century old. It is unlikely, therefore, that all existing networks will be replaced in favour of new, innovative sanitation schemes. The opportunities that are available for future and existing sewer systems are different and will be discussed in the following sections.

5.2 The future of existing sewer systems

Replacement and rehabilitation of sewers is very expensive and can be very disruptive (road closures etc.); the consequence of this is the very slow rate of upgrade. On average, companies in the UK replace/renovate 210 km of critical sewer pipe per year, which would amount to 350 years for the complete repair/replacement of the most critical sewers (Butler and Davies 2011). Therefore, it is not realistic to assume that we should just start afresh, as this would be a huge waste of the infrastructure that has already been created. However, upgrades are eventually going to be necessary for existing systems whether it be because of deterioration, need for expansion, or performance failures and when these situations arise the model developed in this thesis could be useful to help chose the best route towards a more sustainable system upgrade.

5.2.1 Adapting system design

People's water use habits are likely to change in future and water-saving technologies or other water use strategies may be adopted. Water companies could use this model as a tool to better understand the risks in their area and perhaps make decisions to upgrade smaller parts of the system in response to this assessment. Whilst assessing effects of future changes in a specific network, it would be possible to assess the extent in which the system should change to meet service requirements. For example, conducting a simulation with reduced pipe diameters, relined pipes or changing pipe inclines could highlight means for system improvements.

5.2.2 Reducing need for system expansion

As urbanisation increases, sewer systems are in some cases becoming overwhelmed. The example of the Tideway tunnel was discussed in Chapter 3, where the city of London is embarking of a multi-billion-pound project which will expand London's sewer capacity to cope with the dramatic population increase over the last 150 years (Tideway 2019). It has been demonstrated throughout this thesis that there are possible water-saving strategies that could be adopted to reduce the need for expansion. On a case-by-case basis, water companies could use this model to contemplate adopting/encouraging various water use strategies, perhaps identifying areas of the network that are most at risk of overflow. Adopting domestic water-saving strategies could reduce pressure on existing systems and free-up much needed capacity. Better modelling of future scenarios could help to identify specific areas where a change in water-use would be most beneficial.

5.2.3 Review effects for treatment

Better knowledge of the variation in wastewater concentration and quantity and how this is linked to the appliances we chose to install could offer insights for optimising wastewater treatment. As the model offers a greater understanding for how wastewater concentration differs with changing appliances and user habits, the model could be used to plan new treatment strategies, upgrades or expansions into the future. It also offers the option to explore how concentration varies at specific points in the sewer network, offering better information if new decentralised treatment options were being considered. For example, when considering sewer mining as a water recovery option, are there times of the day where this could be employed which would have minimal impact for solids transport and perhaps minimal treatment needed for the water abstracted? Or is there an optimum location in the system where wastewater concentration is high and consistent where resource recovery would be advantageous?

5.3 The future of sewer design in new developments

New developments offer a real opportunity to start afresh with regards to the wastewater systems that are put in place and the appliances that are used. The model developed in this thesis could be particularly helpful in the planning process of new developments. As the sewer is not built yet, planners could get an insight of how the sewer should be designed for a wide range of water use schemes and how this new system might interact with other, older systems that it might be connecting to.

5.3.1 Improved urban water cycle design

Moving into the future it is important to view our water cycles holistically, choosing water use strategies with consideration of both drinking and wastewater systems. The work presented in this thesis has become part of a wider project with TU Delft to model both drinking and wastewater systems simultaneously, with a view to optimise the entire urban water cycle. Figure 5.3-1 outlines a brainstorm of the possibilities that could be realised in our future urban water cycles. It highlights an increase in connectivity between our water flows, for example, community rain collection from local business roofs as these typically have a higher surface area. It also promotes water use of the right quality for right user, use of rainwater and greywater for outdoor and indoor applications that don't require water to be of potable quality. The increased connectivity of the water cycle opens up the option for cultivating more green spaces within urban areas, such as vertical or community gardens and green roofs, which heighten biodiversity and wellbeing. These abstract ideas for the urban water cycle are numerous and planners/developers can choose how ambitious they want to be in specific areas depending on the situation and needs of the area, i.e. business presence, available space etc.

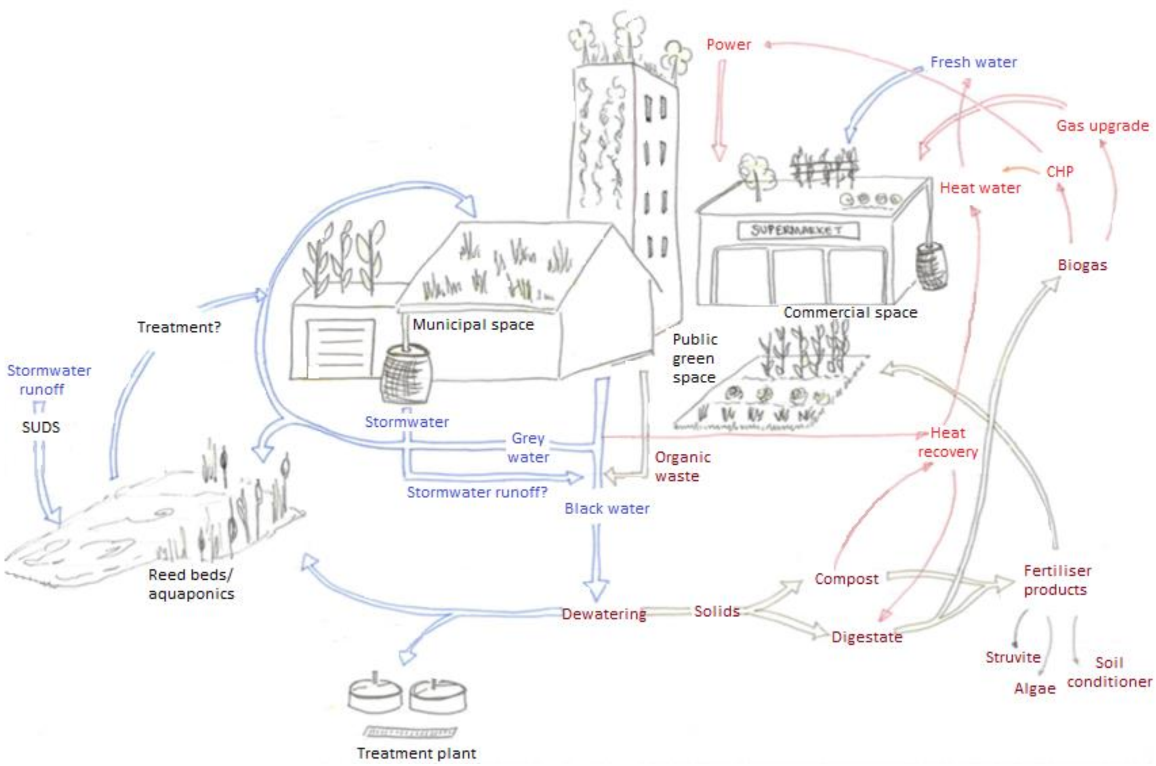

Figure 5.3-1. Flowsheet showing some future possibilities for a future urban wastewater cycle. This cycle considers water flows (blue), nutrient flows (brown) and energy flows (red) that could be integrated to increase the sustainability of urban water cycles. This suggests that wastewater fractions are separated and water reused where possible, nutrients get recovered from the concentrated wastewater discharge and returned to green public spaces (e.g. allotments, parks, green roofs). Stormwater is captured in water butts, green roofs or directed to land via sustainable urban drainage systems, SuDS. Energy could be recovered from wastewater discharge or treatment processes and used to heat other parts of the cycle.

5.3.2 Selecting wastewater treatment options

The model described in this thesis allows the user to explore the flow and wastewater quality implications of applying specific wastewater use scenarios. Before adopting a design, developers could explore many scenarios for more ecological and economical water use. Community-wide rainwater harvesting or greywater reuse schemes could be simulated and new water cycles that suit the area could be developed. What treatment options are available for this new development, knowing the daily profile for flow and wastewater quality? The model results may indicate that wastewater treatment and resource recovery could be dynamic across the day. For example, if nitrogen concentration peaks in the morning but not otherwise throughout the day, the choice could be made to treat that concentrated flow separately and recovery operations targeted during that period. This concept has the potential to optimise design and reduce system size whilst offering cost savings and a more efficient process. It could be an important tool to help deliver the paradigm shift that the urban water cycle is calling for.

5.3.3 Minimising impact of new connections

In rapidly expanding cities, it can often be the case that a new development needs to connect to a sewer that has limited capacity to deal with the increased inflow. In these cases, it is necessary to minimise the new flow of wastewater into the existing system. The water use patterns in new developments (with whatever new technologies are chosen) are likely to have a different diurnal pattern than from older households. With this model, it is possible to simulate properties with very different water use habits and discharges and observe how different discharge regimes interact within the network. This model could help to identify favourable water use scenarios to minimise the impact on the existing flow patterns. For example, if the existing system is already close to capacity in the morning peak, it would be favourable to choose to install appliances in the new development that minimise that peak or appropriately trade-off which water saving techniques is optimal for the flow into the existing system and the cost of installation.

5.4 Model shortcomings

It is important to highlight the model shortcomings in the present day to offer greater awareness to the reliability of the outputs and to draw attention to where the model still needs improvement. This section aims to show that, although this model shows much promise, it should be approached with a degree of caution in its present state and appropriate consideration should be given to the results.

5.4.1 Water use calibration data

The model calibration is now based on average water use from meters installed in households. Metering in the UK is not compulsory and therefore there is not always a high coverage of meters, this reduces reliability of the data to represent the entire area. Meters in the UK are typically read about every three months and the usage is averaged over that time. This misses any information about when water is being used throughout the day and times that the occupants might be away from home. Smart metering would supply more reliable data in which the model could be calibrated against and could be helpful towards a more structured calibration of the SIMDEUM® software, which was developed using Dutch water-use data.

There is also a calibration step that depends on the typical water use distribution amongst household appliances, this data is based on a survey of a very wide area and is likely to miss specific habits of an area. Again, smart metering could mean more reliable data would be available for this in future but it all depends on just how accurate an analysis is required. There are also still questions of just how accurate it is reasonable to expect this analysis to be.

5.4.2 Appliance-specific wastewater quality data

As was discussed in chapter 1 and chapter 3 the wastewater quality element of the model is based on data dating back to the 1970's. It is reasonable to assume that the way we use water and the wastewater quality produced from household appliances has changed a great deal in that time. The present data on this topic covers a very wide range of values which leads to an uncertainty of which are the most relevant values to use. The average discharge data used in the model is currently given to the accuracy of multiple decimal points, this could give a false impression of the uncertainty that is inherent in the values and may lead to conclusions to be more exact than they would realistically be in practice. There is a need for a more up-to-date study on wastewater quality from household appliances in order to better inform this model.

It is also notable that in its current state, the model assumes an average pollutant discharge per appliance. In reality, there is a wide range in wastewater quality that emerges from household appliances and it would significantly strengthen this model to include variable water quality discharged from appliances. The modelling of this could be improved by developing SIMDEUM WW® to select from a range of possible concentrations that are typical from household appliances.

5.4.3 Network modelling of gross solids

As was discussed in Chapter 4, the suspended solids modelling element of InfoWorks® ICM is not currently functioning and will be corrected in a future software edition. This made it difficult to address if the model has the capacity to accurately model wastewater concentration. When this aspect is available it will be important to re-assess the validation data collected for wastewater quality in the sewer network to address if the model can accurately predict wastewater concentration throughout the network.

5.5 References

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Chapter 6

Conclusions and future work

6.1 Conclusions

A paradigm shift is needed in urban wastewater systems to boost sustainability and environmental sensitivity. Going forward, there is an apparent need to conserve water and this could allow us to improve treatment efficiency, capacity and recovery of resources. There is a need to understand the effects that future water use will have on infrastructure to ensure we make the best choices for resilience and sustainability in future planning. Sewer models developed in previous literature had been dependant on measured data and mostly used averaged and continuous discharge patterns for households within the modelled network. Thus, the overarching aim of this thesis was to develop a stochastic sewer model that could be used to observe the changes to wastewater flow and quality that could arise from future water use. This was with a view to improve sustainability within the urban water cycle. This aim was achieved through addressing four core objectives that were outlined in Section 1.7 of this thesis.

The key conclusions obtained through the work presented in this thesis are:

1. A stochastic sewer flow and quality model was developed.

   Stochastic wastewater discharge patterns (using SIMDEUM®) were incorporated into a sewer network model (InfoWorks® ICM) to produce a sewer model that includes unique household discharges that are linked to specific appliances. Appliance-specific wastewater quality profiles were generated and incorporated within the discharge pattern with the use of SIMDEUM WW®. This conclusion demonstrates the completion of objectives 1 and 2 (see Section 1.7).

2. Wastewater flow and quality data was collected to validate the model.

   Case studies in the UK and the Netherlands were used to test and confirm the models performance through the collection of wastewater flow and quality data. A week-long wastewater quality campaign saw the collection of hourly samples to show how concentrations of TSS, TPH, TKN and wastewater temperature changed throughout the day. Although the model agreed well with hydraulic and mass flow data, it did not agree quite so well with the wastewater concentration data. This was due to limitations in the InfoWorks® network model that did not allow the time varying modelling of solids. This meant that the hold-up in the sewer of solid particles was not modelled as real life. This exhibits the completion of objective 3 (see Section 1.7) which set out to calibrate and validate the hydraulic and wastewater quality aspects of the model using physical data.

3. Future water use scenarios were simulated using the model to predict effects to flow wastewater concentration and temperature.

Five future water use scenarios were simulated using the UK- based case study. It was found that the installation of water-saving appliances softened the peaks in sewer discharge which could reduce the size requirements of wastewater systems or alleviate the risk of overflow in the case of increased connections. The scenario testing revealed that for a 15-60% water saving there would be a 1-48% drop in morning peak flow. For the same reduction in water use, the concentrations of COD, TKN and TPH were predicted to increase 55-180%, 19-116% and 30-206% respectively. Although these concentration changes were predicted before the validation of the stochastic wastewater generator.

A further six scenarios were simulated within the Netherlands-based case study. These included three common methods of water conservation (water-saving appliances, greywater reuse and rainwater harvesting). These scenarios reduced water use by up to 62% and reflected concentration increases in COD, TKN and TPH of 111%, 84% and 75% respectively. Installation of water-saving appliances and greywater recycling dramatically reduced the peak flows, whereas rainwater harvesting produced similar flow and concentration results, as in the baseline case. The greywater recycling scenario produced the most consistent wastewater concentrations and the lowest wastewater temperature.

Demonstrating the applications of the model through scenario simulation and producing predictive results for the consequential impacts of those scenarios shows the completion of objective 4, stated in Section 1.7.

4. This work has provided recommendations and implications of water conservation on sewer network design.

This modelling approach could aid planners in adapting existing sewer systems to cope with future demand but it could also be used to assist town planning in the development of new sewer systems, where more dramatic water-savings may be realised. The recommendations for design will vary between systems and are highly dependent on the local situation, thus the model presented in the thesis could contribute to further investigations. This addresses objective 5, as stated in Section 1.7.

6.2 Future work

The work presented in this thesis highlights a model that shows strong potential to better understand the effects of changes in future water use on the wastewater system. Although the model shows promise, there are a few areas where it would be sensible to continue developing and a huge variety of scenarios and impacts that it could be used to explore. The main areas highlighted for future development are detailed below:

1. Time-varying suspended solids modelling

As explained in Chapter 4, it was discovered that InfoWorks® ICM did not have the capability to model the time-varying solids input. Innovyze (the InfoWorks® developer) has advised that this was a software error and this capability will included in a new software release. Therefore, it would be valuable to run the scenarios again within the new software version to check if the prediction of wastewater concentration can be improved. As wastewater concentration and solids transportation is so important for the acceptance of water use changes it is important to develop this area of the model.

2. Develop a wastewater quality range for the appliance-specific discharges.

Currently, the appliance discharge concentrations are constant with each appliance type. Although some appliances would produce a very similar pollutant mass for each use, in some cases, i.e. the toilet, the difference between uses could be much larger. Urine for example is very nutrient rich whereas faeces is solid and rich in COD. Another example is the washing machine, the wash cycle discharge would have a high concentration of detergent and dirt but subsequent rinse cycles would be much more dilute. The modelling of this could be improved by developing SIMDEUM WW® to select from a range of possible concentrations for these appliances or be able to specify at which point of the discharge process the pollutants are concentrated.

3. Integrate weekend modelling

To date, only the weekdays have been modelled. To have a full picture of a future water use scenario it would also be important to consider the weekends. It is not currently possible to utilise SIMDEUM WW® to convert the weekend demand patterns into discharge profiles, this would be a development in the SIMDEUM WW® code. It is also worth noting that the probability data in which SIMDEUM® is based was collected for weekdays and only the time at which people schedule their time changes. More data would need to be collected to better define how people use appliances at the weekend as this likely follows different habitual tendencies than the weekdays.

4. Modelling of further scenarios and various levels of acceptance

This model offers a large amount of flexibility with regards to the scenarios that it is possible to simulate. In this thesis, a small selection of scenarios have been shown and with the situation in which 100% penetration is achieved. It is more likely that water use changes occur through a more gradual, scattered process with many people using different schemes (unless community actions or new legislation intervene). There are many scenarios that could still be explored for their effects on wastewater concentration and flow using this model, for example, the installation of food waste grinders. Through this work, a collaboration was formed with a research group in Delft University of Technology (TU Delft), the Netherlands, which involved linking this sewer model with a similar drinking water model to observe these future water use scenarios in a more holistic way that could help decision-makers to assess future development options with a full-cycle perspective.

It is also proposed that this model could be used in the design of the wastewater systems in a new housing development (Filton Airfield Development). This is a new development in which Wessex Water are designing the sewerage and wish to maximise sustainability. Demonstrating the use of this model for this project both in design phase and post-development could greatly increase confidence.

5. Random allocation of households within the model

Discharge profiles, produced in SIMDEUM WW®, are currently assigned to households within the network manually. Therefore, when testing a selection of water-saving methods at the same time the distribution of water-use among the population could be biased. This could be improved by incorporating a random allocation process to assign discharge patterns to households within the network.

Appendix

Modelling algorithm

Modelling algorithm

This appendix outlines the modelling algorithm used within this work and highlights the key information flow between InfoWorks ICM® and SIMDEUM®.

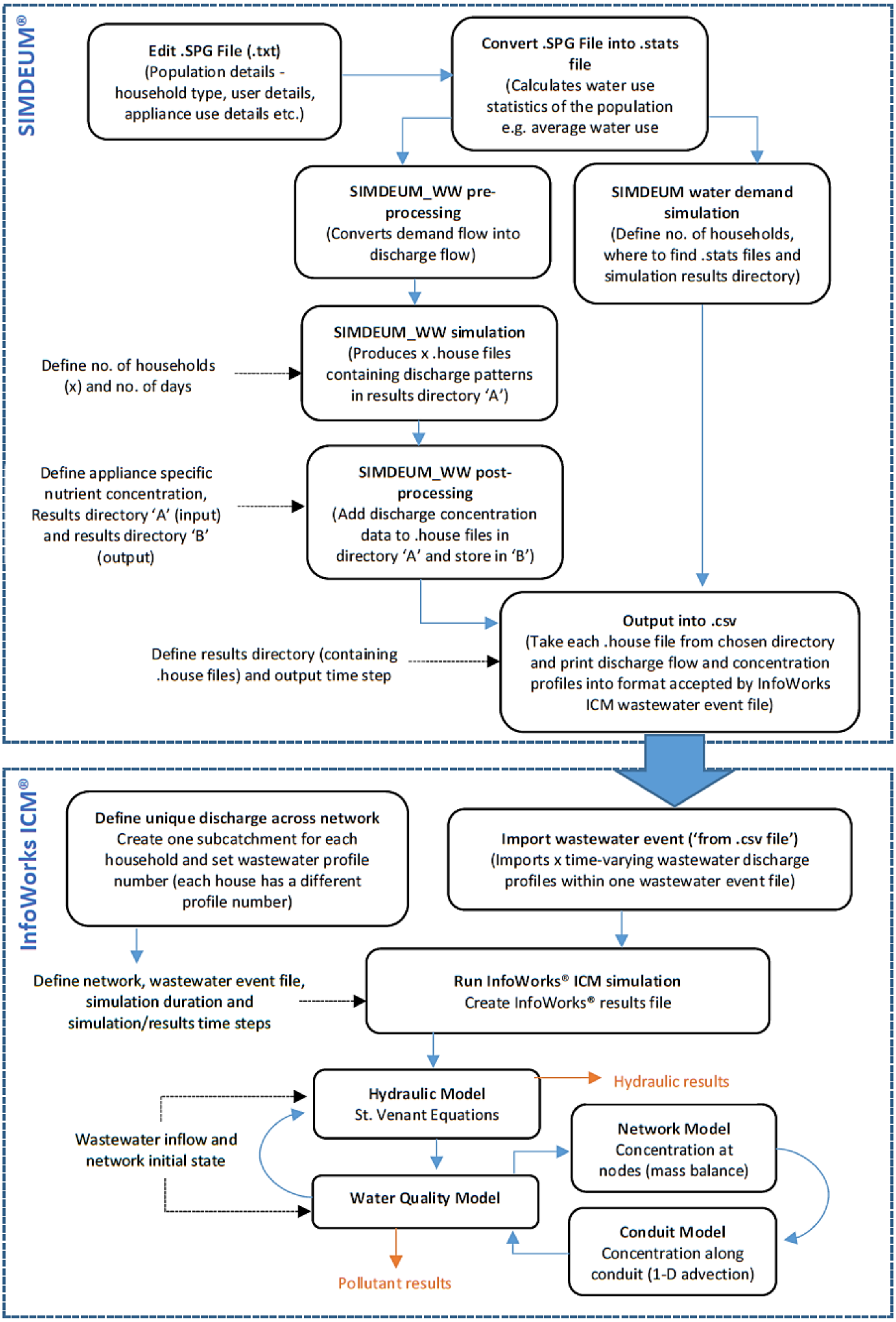

Figure A-1. Flowchart showing algorithm of modelling activity in SIMDEUM® and InfoWorks® ICM