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ABSTRACT

Population growth and climate change put a 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 was predicted to increase wastewater concentrations of chemical oxygen demand (COD), total Kjeldahl nitrogen (TKN) and total phosphorus (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.

Key words | appliance-specific discharge, future water use, sewer design, stochastic sewer modelling, wastewater concentration, wastewater quality modelling

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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), but 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.

Aside from saving water, increasing wastewater concentration is also an attractive concept for sustainability. Recovering resources from waste is becoming much more relevant for water companies worldwide (Billund BioRefinery 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 the more concentrated household wastewater and make resource recovery from wastewater more effective (Hernández Leal *et al.* 2010; Verstraete & Vlaeminck 2011; Diamantis *et al.* 2013; Tolksdorf & Cornel 2017). Options range from the decentralisation of wastewater treatment to re-concentration at the wastewater treatment plant

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(WWTP). Verstraete & Vlaeminck (2011) stated that preferable options would be to prevent dilution of wastewater in the sewer via the use of separated sewer systems, reduced infiltration rates or add kitchen waste to sewage to boost nutrient concentrations. It was suggested that reducing water consumption by 25% in a separated 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 lead to the 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 & 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 sewage system 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 combined sewer overflow (CSO) potency under various water conservation measures. They used a deterministic input profile for domestic wastewater generation and promoted the sustainability of rainwater harvesting as a future strategy because it ensured the dilution of wastewater in comparison to other water conservation strategies (i.e. reduced potency CSOs 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% chemical oxygen demand (COD), 7–73% total suspended solids (TSS), 9–57% ammonium nitrogen (NH_4-N) and 7–52% phosphate phosphorus (PO_4-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 second) and spatial (customer tap) scales, which 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 is 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 to 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 the 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) were 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 is 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 are presented and analysed. This is followed by the key conclusions from this work.

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 *et al.* 2010; Blokker 2011) 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.

Household discharge modelling

Hydraulic discharge

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.

Water quality loading

Following the development of the flow discharges to the sewer, SIMDEUM WW® was used to associate water quality with 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 that study included a review of other literature to assess typical appliance concentrations (Siegrist *et al.* 1976; Butler *et al.* 1995; Surendran 1998; Parkinson 1999). 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 & Agudelo-Vera (2015). The toilet pollutant quantities were found by taking the average mass discharge from toilets a variety of toilet flush volumes (2 or 4 L (dual), 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 1.

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

Table 1 | Appliance-specific discharge parameters used in the improved SIMDEUM WW® wastewater quality profiles

		Sewage quality (g use^{-1})				
Appliance	**Temp. (°C)**	**COD**	**TKN**	**TPH**	**TSS**	**Explanation**
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)

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.

aspect of the Infoworks ICM® model occurs in parallel to the hydraulic model, transporting determinants and sediment through the drainage system. At each timestep, 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. 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. 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®.

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 those 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 in a range of sizes: 100 mm, 150 mm and 225 mm (representing 52%, 26% and 22% of the total pipe length, respectively). Each size class had the average slope of 1:61 (ranging from 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 catchment studied, as well as calibration and validation of the flow model, can be found in Bailey *et al.* (2019).

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 been 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) 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 has been described in Table 2.

The water savings described in these five scenarios have been quantified on an appliance-specific basis by Artesia

Table 2 | Future scenario description; scenarios were produced by Artesia Consulting on behalf of OFWAT (Artesia 2018)

Scenario	Demand[a] (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 pushing lower volume toilets and uptake of recycling/digital showers, regulation and water labelling delivering more efficient machines.

[a]These figures include system losses that have been omitted from the household simulations.

(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 the discharge volume of an appliance, or by defining new appliance characteristics (e.g. waterless washing machines or non-potable flush toilets). Figure 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 part of scenarios 3 and 4: 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 at zero). Once calibrated with the water input the households were simulated again including the non-potable appliances, which 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 was 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.

RESULTS AND DISCUSSION

Hydraulic modelling for future water use scenarios

Figure 2 shows how the water use scenarios presented 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 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 are set out for each scenario in Table 3.

It can be seen from Table 3 that decreases in water use between 15 and 60% could amount to a 1–48% drop in the morning peak. These peak impact estimates are more conservative than those presented by Penn et al. (2012), who conducted a similar analysis using a deterministic model.

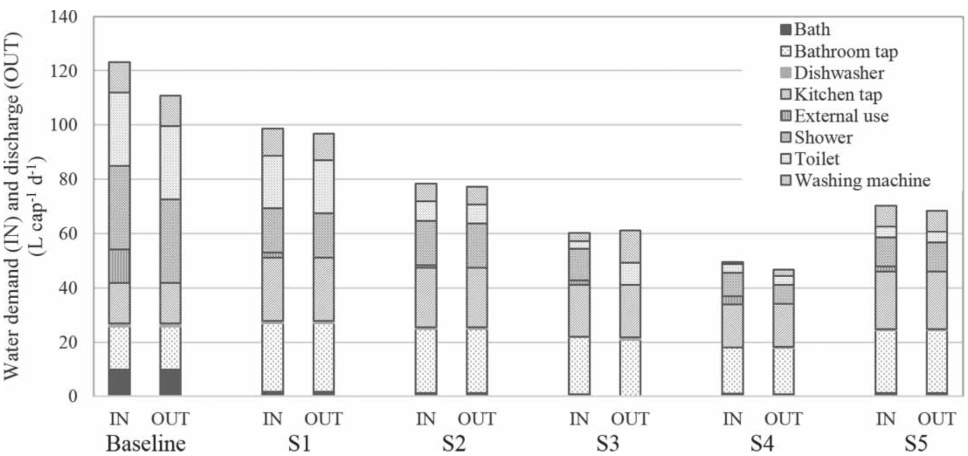

Figure 1 | Outline of appliance demand and discharge for each of the future scenarios (appliance inputs from Artesia (2018)).

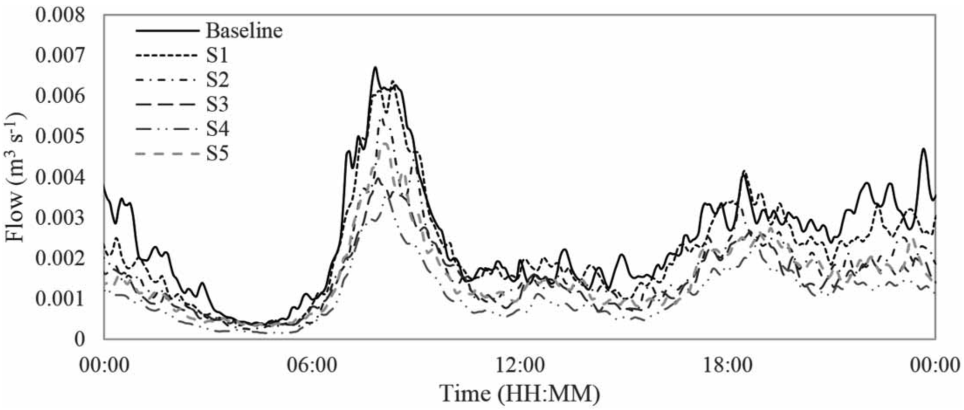

Figure 2 | Variation in weekday wastewater flow patterns at the catchment outfall resulting from future water use scenarios.

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 lower 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 model presented: that every modelled household is unique, which allows a variety of appliances to be modelled simultaneously, i.e. some household 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 affects the entire flow pattern equally.

Table 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

Table 3 | Outlining the effect that various water use scenarios have on peak and average sewer flow, velocity and depth at the catchment outfall

	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%

This is the outcome from the simulation of a single week. Each effect has been compared to the validated baseline model.

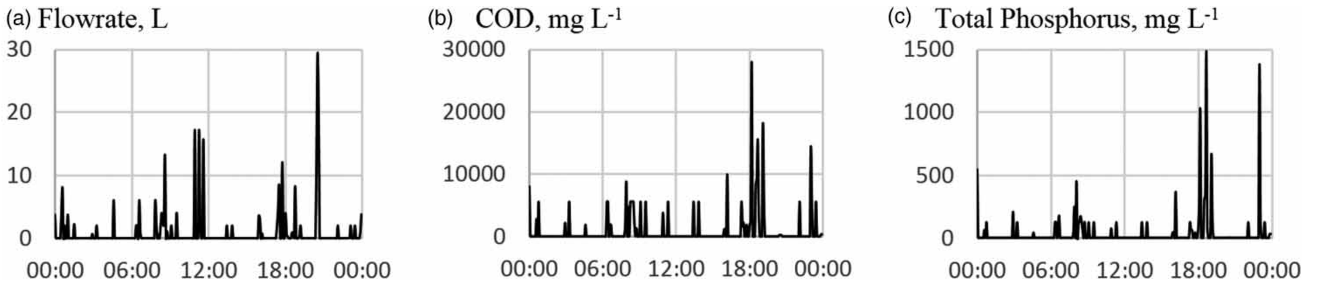

Figure 3 | Example daily pollutant discharges from a household generated using SIMDEUM WW®.

shallowing of the morning peak could take the pressure off existing infrastructure if future populations increase or new developments are built, 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.

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 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.

Table 4 quantifies how average wastewater concentration varied between future scenarios. Pollutant profiles have been shown for COD, total Kjeldahl nitrogen (TKN), total phosphorus (TPH) and wastewater temperature as these are parameters that are most important for making 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 lower 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 decrease in pollutant load through greywater treatment and garden irrigation. Increased nutrient concentration comes with lower wastewater temperatures in the cases that utilise GWR as shower/bath water is no longer discharged to the sewer.

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 a higher

Table 4 | Quantifying the impact that future water use scenarios have on wastewater concentration at the catchment outfall

	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%
Average (1% trimmed)						
COD ($mg\ L^{-1}$)	1,601	2,484	2,519	3,145	4,485	2,653
% 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%

Each concentration change has been given in comparison to the baseline scenario.

concentration of nitrogen than scenarios 1 and 2 but 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 much-reduced loads due to greywater pre-treatment. Table 4 presents the 1% trimmed average from a week-long simulation in order to show the most typical average concentration from each scenario. Scenario 5 produces the lowest average (1% trimmed) nitrogen concentration, which is thought to be due to most of the flow reductions being due to 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 trimmed average.

Figure 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 & 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 2,750 mg COD L^{-1}, 184 mg TKN L^{-1} and 35 mg TPH L^{-1} were reported. In comparison to the results presented in this study, phosphorus is the only parameter that was over-predicted, which is likely due to a difference in washing detergents used in the studies, which considered detergents to be the major input of TPH. The mass balance on total pollutants produced using SIMDEUM WW® also matches data

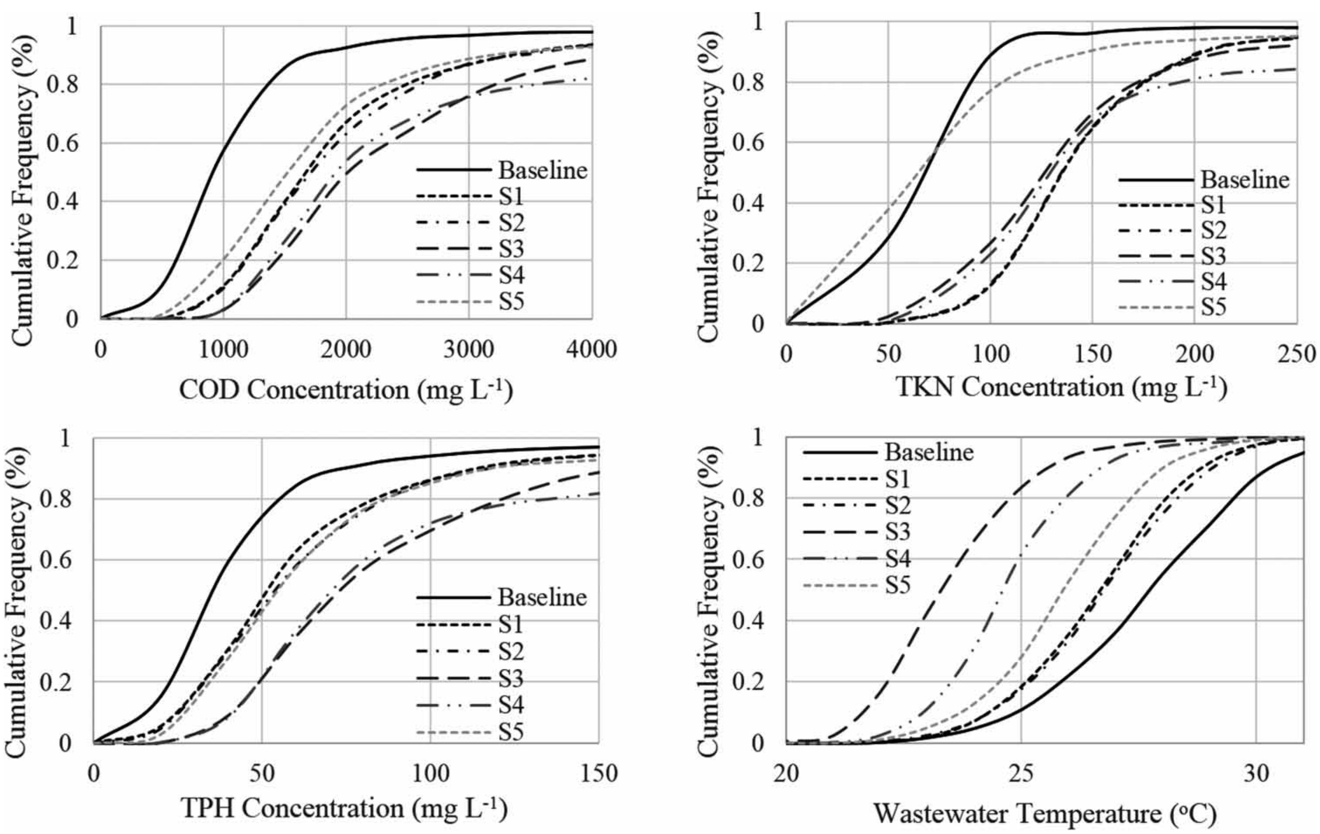

Figure 4 | Variation in wastewater quality parameters (COD, TKN, TPH concentration and wastewater temperature) obtained with the stochastic water quality model at the catchment outfall.

found for the typical mass of pollutants produced per person (Tchobanoglous & Burton 1991; Henze et al. 2008). Henze et al. (2008) published daily per capita loads 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, 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, and water use habits and appliances have changed. For example, there have been recent changes in EU legislation to reduce phosphorus use in detergents (Regulation (EU) No. 259/2012) and a study conducted by Arildsen & Vezzaro (2019) noted a decrease in wastewater phosphorus concentrations over recent years. It is therefore a recommendation from this study that more recent data are collected on appliance-specific wastewater concentrations.

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 (faeces and urine respectively) and concentrations but they are 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, so would be a significant step forward in modelling accuracy.

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 in 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, which 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 a 55–180% rise in COD, a 19–116% rise in TKN and a 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.

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