Delft University of Technology

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

Bailey, O.; Arnot, T. C.; Blokker, E. J.M.; Kapelan, Z.; Vreeburg, J.; Hofman, J. A.M.H.

DOI
10.1016/j.jhydrol.2019.04.013

Publication date
2019

Document Version
Accepted author manuscript

Published in
Journal of Hydrology

Citation (APA)
Bailey, O., Arnot, T. C., Blokker, E. J. M., Kapelan, Z., Vreeburg, J., & Hofman, J. A. M. H. (2019). Developing a stochastic sewer model to support sewer design under water conservation measures. *Journal of Hydrology*, *573*, 908-917. https://doi.org/10.1016/j.jhydrol.2019.04.013

Important note
To cite this publication, please use the final published version (if applicable).
Please check the document version above.

Copyright
Other than for strictly personal use, it is not permitted to download, forward or distribute the text or part of it, without the consent of the author(s) and/or copyright holder(s), unless the work is under an open content license such as Creative Commons.

Takedown policy
Please contact us and provide details if you believe this document breaches copyrights.
We will remove access to the work immediately and investigate your claim.

This work is downloaded from Delft University of Technology.
For technical reasons the number of authors shown on this cover page is limited to a maximum of 10.

ACCEPTED MANUSCRIPT

Developing a Stochastic Sewer Model to Support Sewer Design under Water Conservation Measures

O. Bailey[1*], T.C. Arnot[1], E.J.M. Blokker[2], Z. Kapelan[3,4], J. Vreeburg[3,5], J.A.M.H. Hofman[1]

[1] Water Innovation & Research Centre, Dept. of Chemical Engineering, University of Bath, Claverton Down, Bath, BA2 7AY UK

[2] KWR Watercycle Research Institute, PO Box 1072, 3430 BB Nieuwegein, The Netherlands

[3] Department of Water Management, Faculty of Civil Engineering and Geosciences, Delft University of Technology, Delft, The Netherlands

[4] College of Engineering, Mathematics & Physical Sciences, University of Exeter, Exeter, UK

[5] Evides Water Company, PO Box 4472, 3006 AL Rotterdam, The Netherlands

*Corresponding Author: O.Bailey@bath.ac.uk

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

© 2019 Manuscript version made available under CC-BY-NC-ND 4.0 license
https://creativecommons.org/licenses/by-nc-nd/4.0/

ACCEPTED MANUSCRIPT

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 velocity and pollutant concentrations because of 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.

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

1 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

ACCEPTED MANUSCRIPT

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 aiming 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

ACCEPTED MANUSCRIPT

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 grey water 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) 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,

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

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. The case study simulated using the model is described in Section 3. The output from the stochastic sewer model is presented and analysed in Section 4, 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 5.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

2 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 3). 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.

2.1 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 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 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 whilst producing likely discharge pulse flows into the sewer.

ACCEPTED MANUSCRIPT

2.1.1 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.

2.1.1.1 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 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 2010-2017, and error analysis between cumulative frequency plots (see Equation 1) facilitated comparison between water use distribution in the observed data and predicted water use.

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

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

Table 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

ACCEPTED MANUSCRIPT

the SIMDEUM® software. The usage profiles for Catchments A and B have been created for the studied catchment, described in Section 3, through the calibration process.

(Figure 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 1: Outline of appliance usage in SIMDEUM® scenarios)

2.1.1.2 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 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, 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, therefore discharge patterns were calibrated using only data on the division of household type (central pie chart in Figure 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, it was possible to shift the division shown in the central pie chart (Figure 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.

ACCEPTED MANUSCRIPT

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

(Table 2: Differences in household occupancy between SIMDEUM® average and the case study)

2.2 Hydraulic sewer modelling

The sewer network studied, see Section 3, was simulated 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.

2.2.1 Preparing the network model for stochastic discharge patterns

The network model was based on asset data received from Wessex Water (Section 3) and modelled using InfoWorks ICM (Sewer Edition; Innovyze Ltd, Oxfordshire). Wastewater discharge profiles, generated using the methodology described in Section 2.1, were used here as an input into the sewer model. 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 2.1.

2.2.2 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

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

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 1250 mm and 800 mm width) 2750 mm from the manhole cover. Depth (accuracy ±0.2 %) and velocity (accuracy ±2.5 %) readings were averaged over 2 minute intervals. Following the removal of any erroneous results, flow results were produced using the 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 flow meter see Section 3.

2.2.3 Future scenario testing

The stochastic sewer model was developed for observing the impacts on 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 flushing 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}, and 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 225 mm (representing 52 %, 26 % and 22 % of the total pipe length, respectively). These size classes had average slopes 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.

ACCEPTED MANUSCRIPT

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 $m s^{-1}$ and depth was equal to or less than 0.01 m, as this is the minimum required to ensure the stability of the InfoWorks model. Time spent below these thresholds was compared for the continuous, present day stochastic model and the future, eco model.

3 CASE STUDY

3.1 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 3. The area marked 'Catchment A' serves around 200 households and was divided into smaller sub-catchments 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 where developed separately (Section 2.1.1.1). Table 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 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 3 mm for the bottom third) and connection angles.

(Figure 3: Map of modelled sewer catchment and the flow meter (FM14))

4 RESULTS AND DISCUSSION

4.1 Calibration of stochastic discharge model to UK situation

4.1.1 Calibrating stochastic household discharge patterns

Figure 4 shows a cumulative frequency plot of the simulated and measured water demands of different scenarios. It also shows the calibrated frequency plot for the study 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 2.1.1, 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 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 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

ACCEPTED MANUSCRIPT

occupancy of households therefore lower water use in the holiday season is not accounted for.

(Figure 4: Performance of SIMDEUM calibration for use in a UK stochastic sewer input model)

4.1.2 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. Figure 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 5). The stochastic model (right side of Figure 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 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.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

(Figure 5: A comparison between continuous and stochastically generated wastewater profiles in selected network pipes (Catchment A))

4.2 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 3). A visual comparison between the observed data and the simulation results can be seen in Figure 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 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

ACCEPTED MANUSCRIPT

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 6: Monday-Friday validation of sewer model using flow, depth and velocity monitoring at the exit of the catchment (FM14))

4.3 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 is compared with the standard calibrated model in Figure 7. The low water use scenario presented is a SIMDEUM® default scenario, here named 'Stochastic - Eco', this is the same 'eco' house scenario 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 1. At 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 0.7 m s^{-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

ACCEPTED MANUSCRIPT

sees water use drop to 30 %, whereas the evening profile remains more similar for both cases. Depth and velocity in the 'eco' case drop by 60 to 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 7: Daily variation in flow, depth and velocity at the outfall - comparing present and future water use)

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 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. Table 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 in the network. The difference in stagnation between the 'present' and 'eco' cases is largest in the 150 mm 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 pipes 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, which 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

ACCEPTED MANUSCRIPT

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.

(Figure 8: Flow in an upstream pipe – a comparison between continuous, stochastic present and future water use modelling scenarios – 11 household connections)

(Table 3: Analysis of stagnation in sewers as a result of changes in water use)

5 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. This 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 out 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.

This 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

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

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 (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.

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.

The authors acknowledge Wessex Water for providing the sewerage data utilised in this work.

REFERENCES

Agudelo-Vera, C., Blokker, E.J.M, Vreeburg, J.H.G., Bongard, T., Hillegers, S., van der Hoek, J.P., 2014. Robustness of the Drinking Water Distribution Network under Changing Future Demand. Procedia Engineering 89: 339-346.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Anglian Water, 2017. "Our Innovation Shop Window." Retrieved 7th June, 2017, from http://www.anglianwater.co.uk/about-us/shop-window.aspx.

Blokker, E.J.M., Vreeburg, J.H.G., van Dijk, J.C., 2010. Simulating Residential Water Demand with a Stochastic End-Use Model. Journal of Water Resources Planning and Management, 136(1): 19-26. DOI:10.1061/(ASCE)WR.1943-5452.0000002

Blokker, E.J.M., 2011. Stochastic water demand modelling; Hydraulics in water distribution networks. IWA publishing, London.

Blokker, E.J.M., Agudelo-Vera, C., Moerman, A., van Thienen, P., Pieterse-Quirijns, I., 2017. Review of applications for SIMDEUM, a stochastic drinking water demand model with a small temporal and spatial scale. Drinking Water Engineering and Science, 10(1-12). DOI:10.5194/dwes-10-1-2017

Brown, R., Keath, N., Wong, T., 2008. Transitioning to Water Sensitive Cities : Historical , Current and Future Transition States. International Conference on Urban Drainage: 1-10.

Butler, D., Davies, J.W., 2011. Urban Drainage. Spon Press (Taylor & Francis), Oxon and New York.

Butler, D., Davies, J.W., Jefferies, C., Schütze, M., 2003. Gross solid transport in sewers. Proceedings of the Institution of Civil Engineers - Water and Maritime Engineering, 156(2): 175-183. DOI:10.1680/wame.2003.156.2.175

Detectronic (2018), from https://www.detectronic.org/.

Elías-Maxil, J.A., van der Hoek, J.P., Hofman, J., Rietveld, L., 2014. A bottom-up approach to estimate dry weather flow in minor sewer networks. Water Sci. Technol., 69(5): 1059-1066. DOI:10.2166/wst.2014.010

Energy Saving Trust, 2013. At Home with Water.

Gormley, M., Campbell, D.P., 2006. Modelling water reduction effects: Method and implications for horizontal drainage. Build Res Inf, 34(2): 131-144. DOI:10.1080/09613210500493031

Marlow, D.R., Moglia, M., Cook, S., Beale, D.J., 2013. Towards sustainable urban water management: A critical reassessment. Water Res., 47(20): 7150-7161. DOI:10.1016/j.watres.2013.07.046

ACCEPTED MANUSCRIPT

Office of National Statistics, 2011. UK Census Data.

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

Penn, R., Schütze, M., Friedler, E., 2013. Modelling the effects of on-site greywater reuse and low flush toilets on municipal sewer systems. Journal of Environmental Management, 114: 72-83. DOI:http://dx.doi.org/10.1016/j.jenvman.2012.10.044

Penn, R., Schütze, M., Friedler, E., 2014. Assessment of the effects of greywater reuse on gross solids movement in sewer systems. Water Sci. Technol., 69(1): 99-105. DOI:10.2166/wst.2013.555

Penn, R., Schütze, M., Gorfine, M., Friedler, E., 2017. Simulation method for stochastic generation of domestic wastewater discharges and the effect of greywater reuse on gross solid transport. Urban Water Journal, 14(8): 846-852. DOI:10.1080/1573062X.2017.1279188

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

Pouzol, T., Bertrand-Krajewski, J.-L., Levi, Y., 2015. Stochastic modelling of dry weather flow in an extensive sewer network using individual behaviour.

Sun, J., Hu, S., Sharma, K.R., Bustamante, H., Yuan, Z., 2015. Impact of reduced water consumption on sulfide and methane production in rising main sewers. Journal of Environmental Management, 154: 307-315. DOI:10.1016/j.jenvman.2015.02.041

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

Watershare, SIMDEUM® from https://www.watershare.eu/tool/water-use-info/

WATERWISE, 2016. "Saving water at home." Retrieved March 1, 2016, from http://www.waterwise.org.uk/pages/at-home.html.

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

UKWIR, 2016. Our Research ''Big Questions''. Retrieved 23rd May, 2017, from https://www.ukwir.org/172496.

ACCEPTED MANUSCRIPT

Figure 1

ACCEPTED MANUSCRIPT

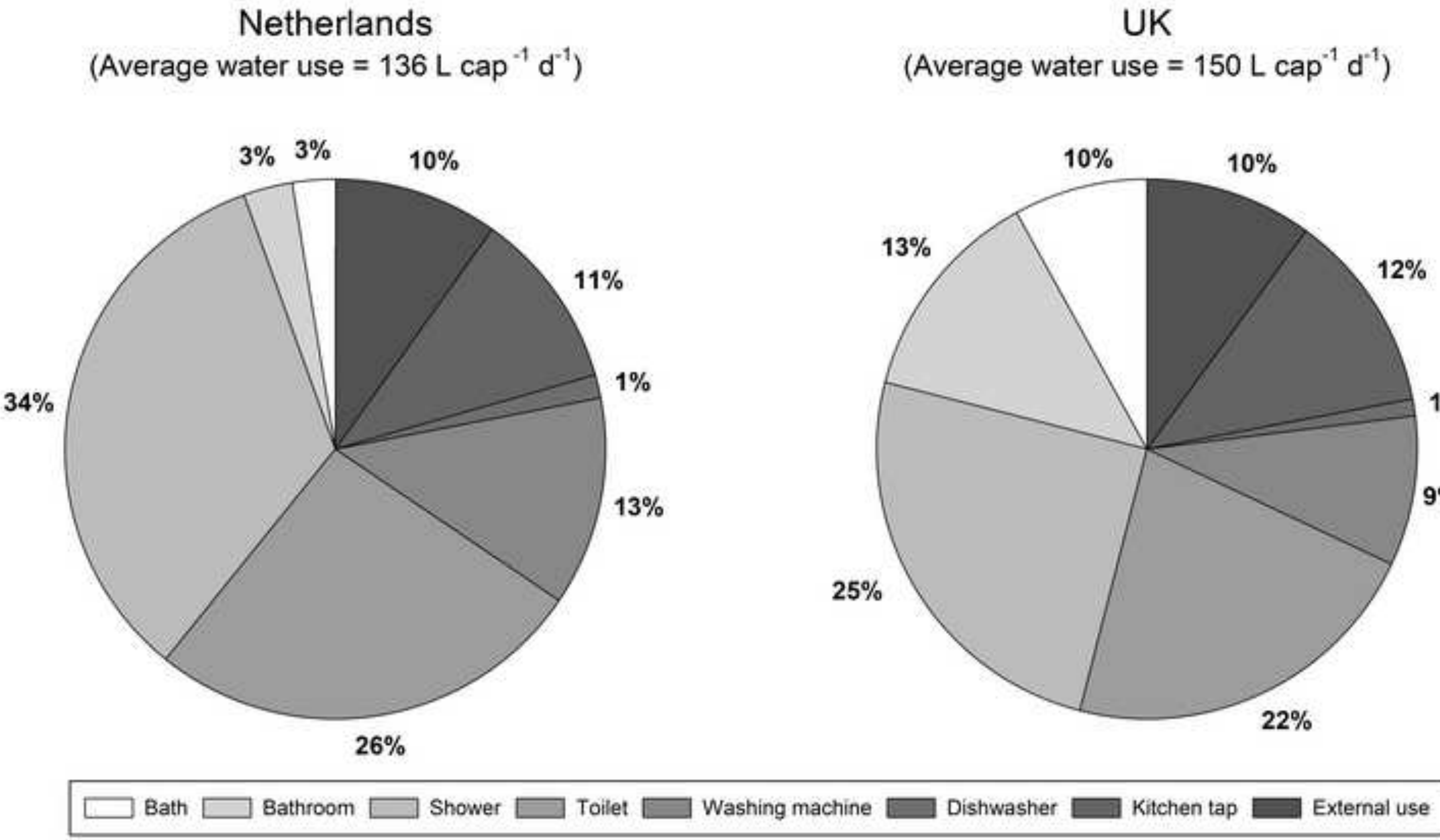


Figure 2

ACCEPTED MANUSCRIPT

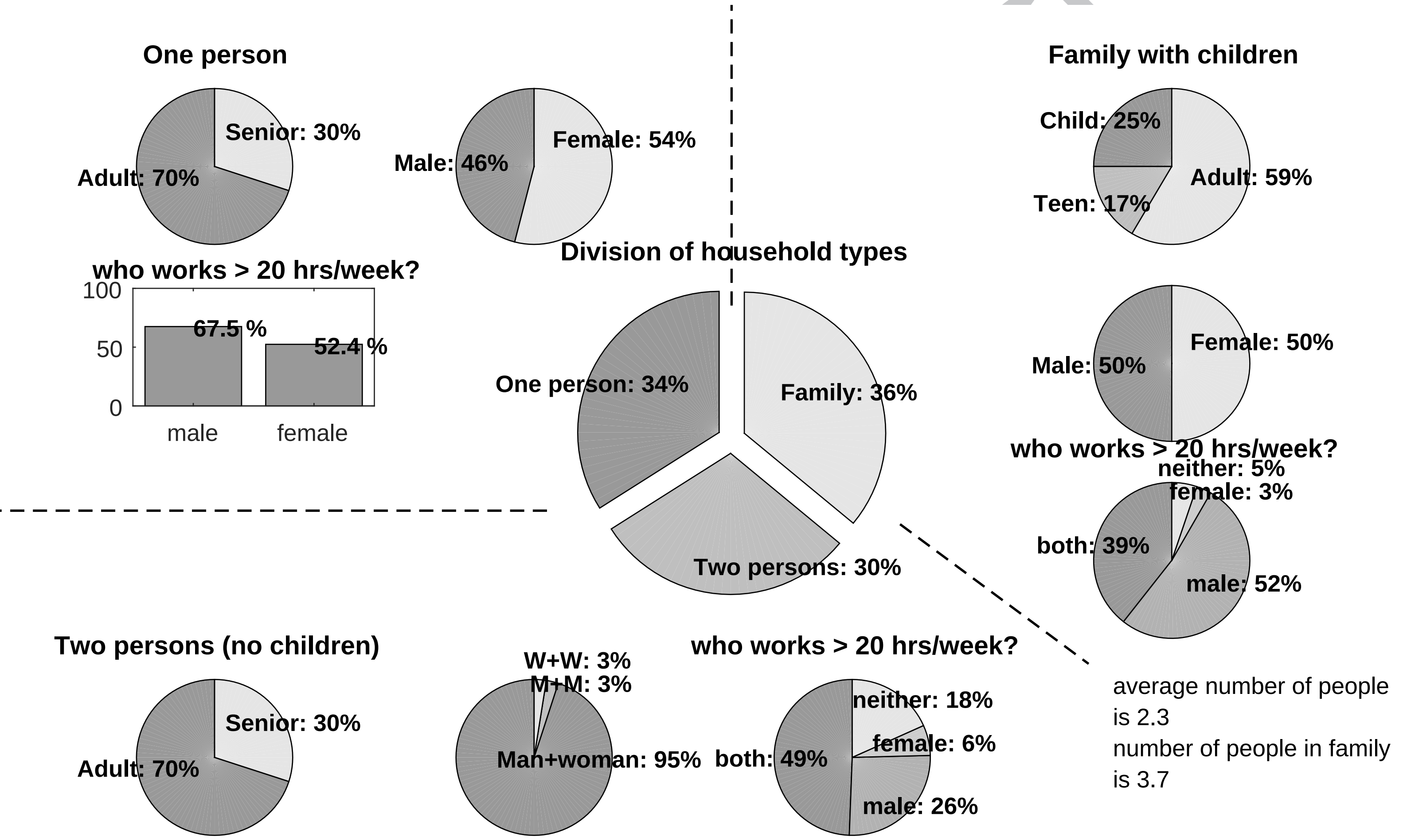
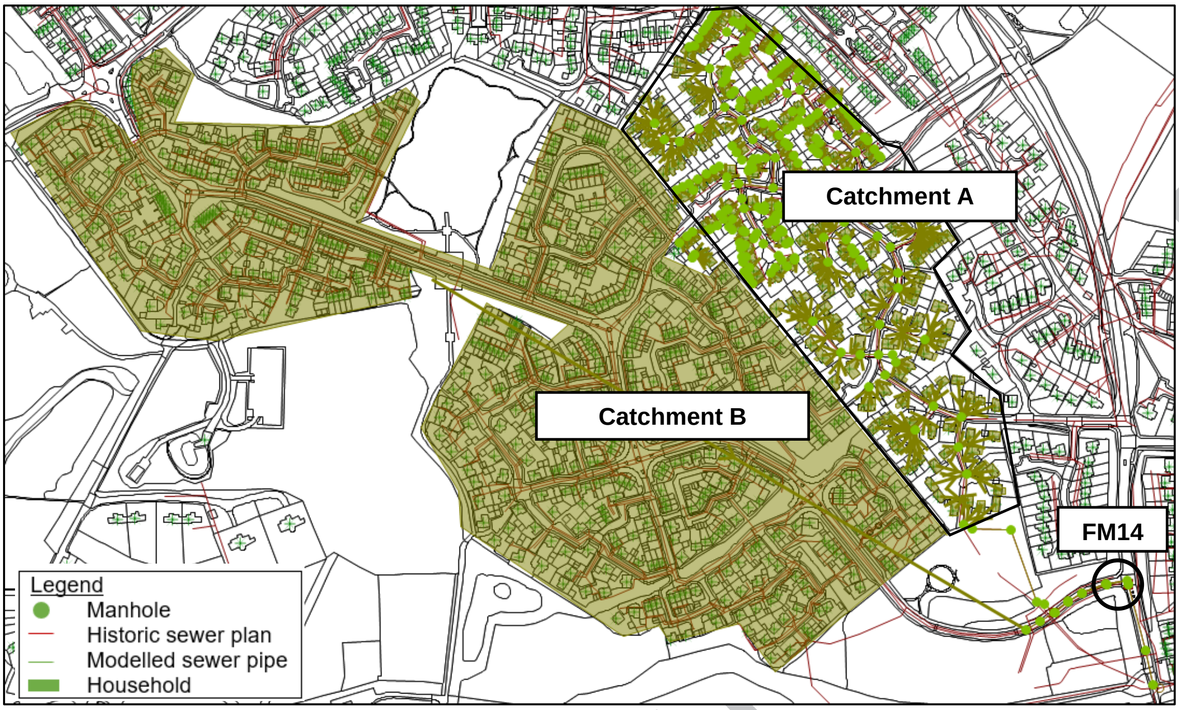


Figure 3

ACCEPTED MANUSCRIPT



ACCEPTED MANUSCRIPT

Figure 4

ACCEPTED MANUSCRIPT

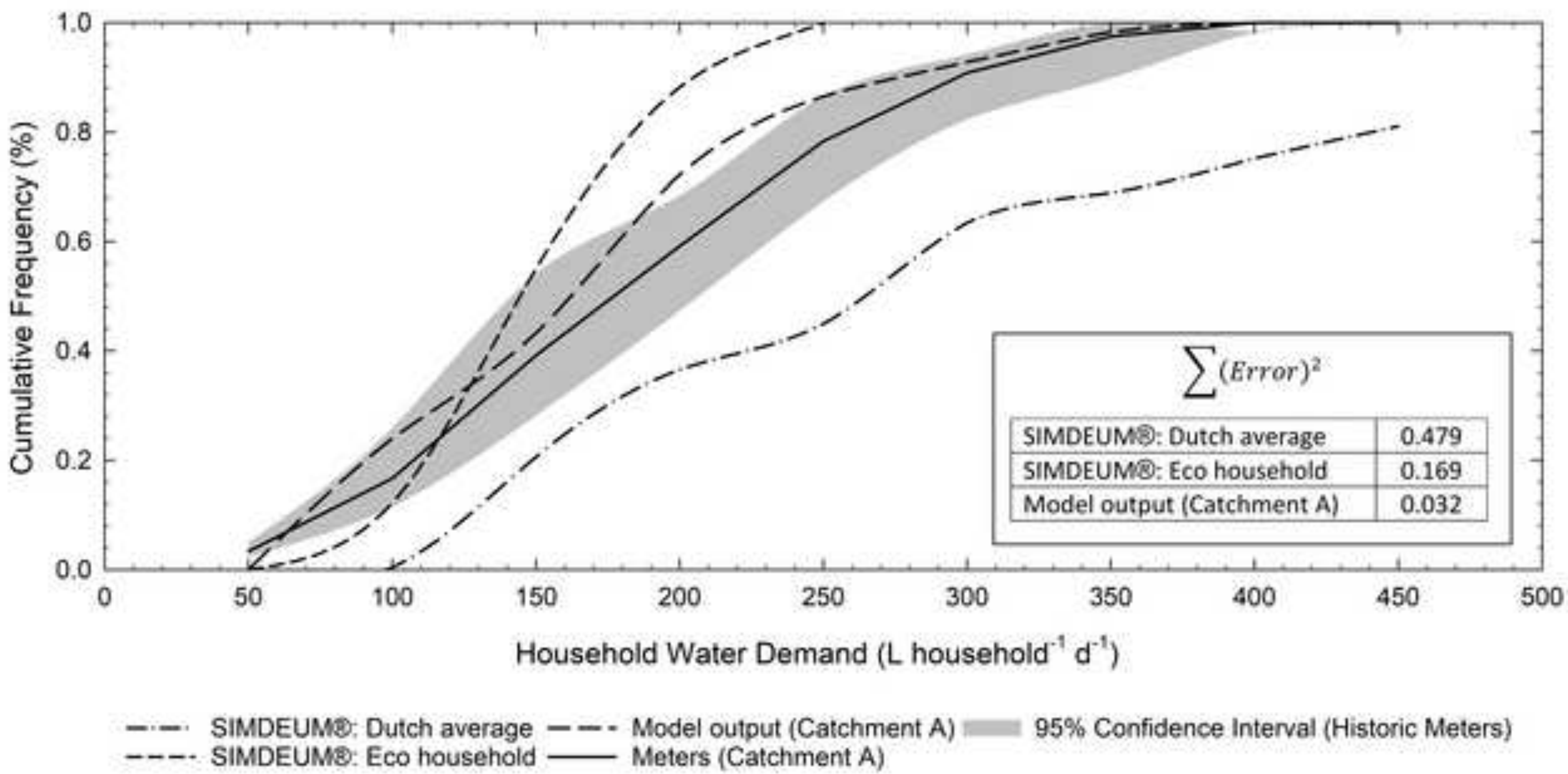


Figure 5

ACCEPTED MANUSCRIPT

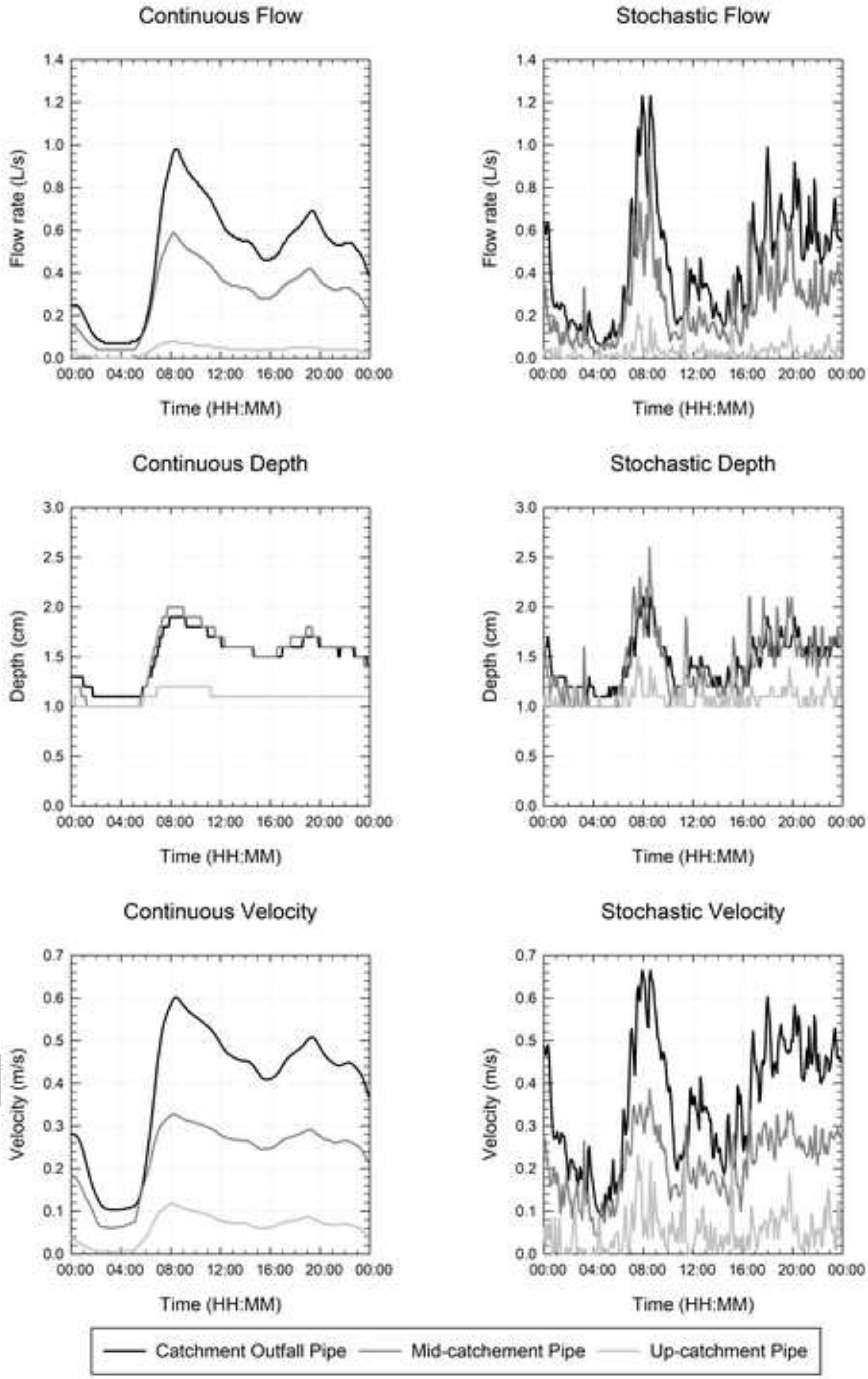


Figure 6

ACCEPTED MANUSCRIPT

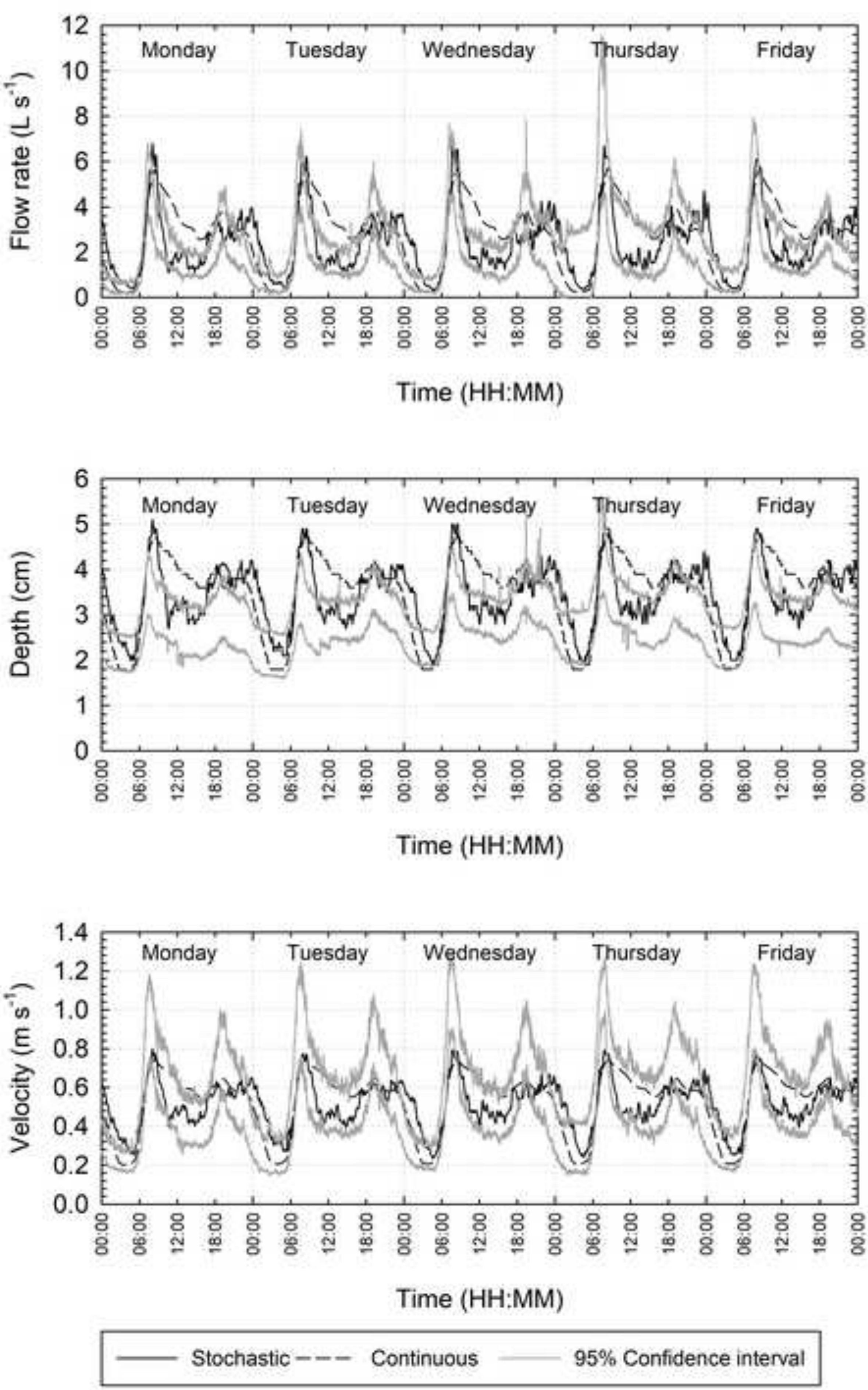


Figure 7

ACCEPTED MANUSCRIPT

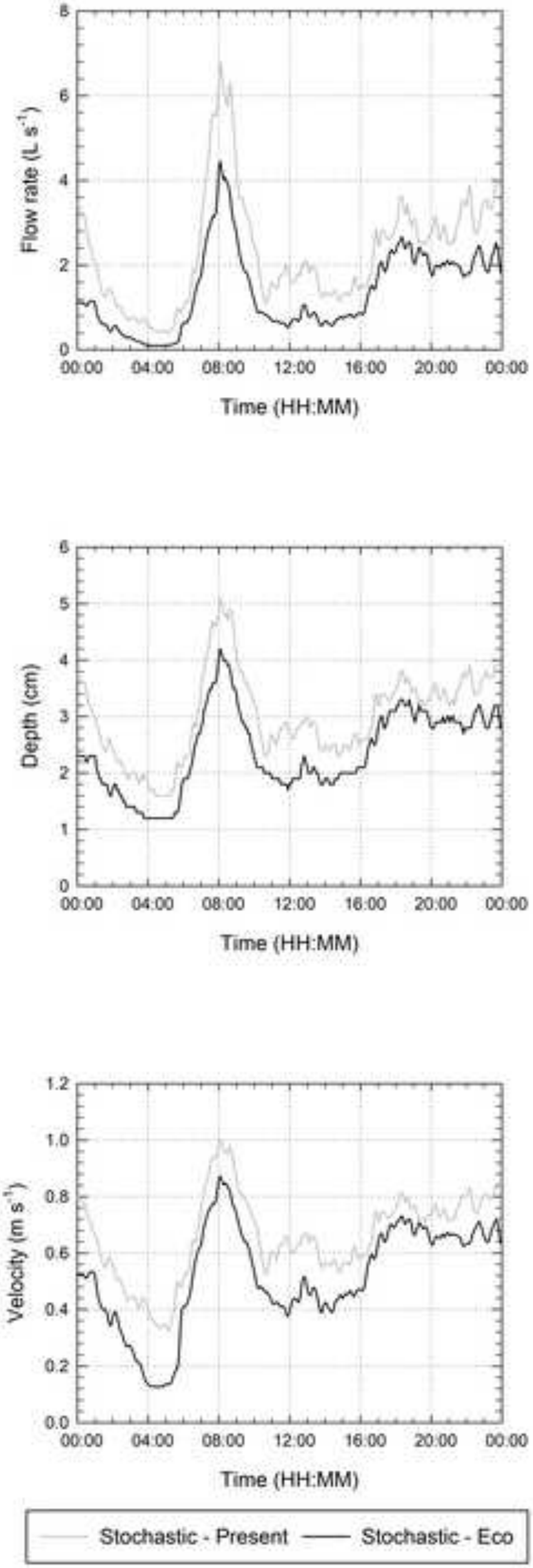
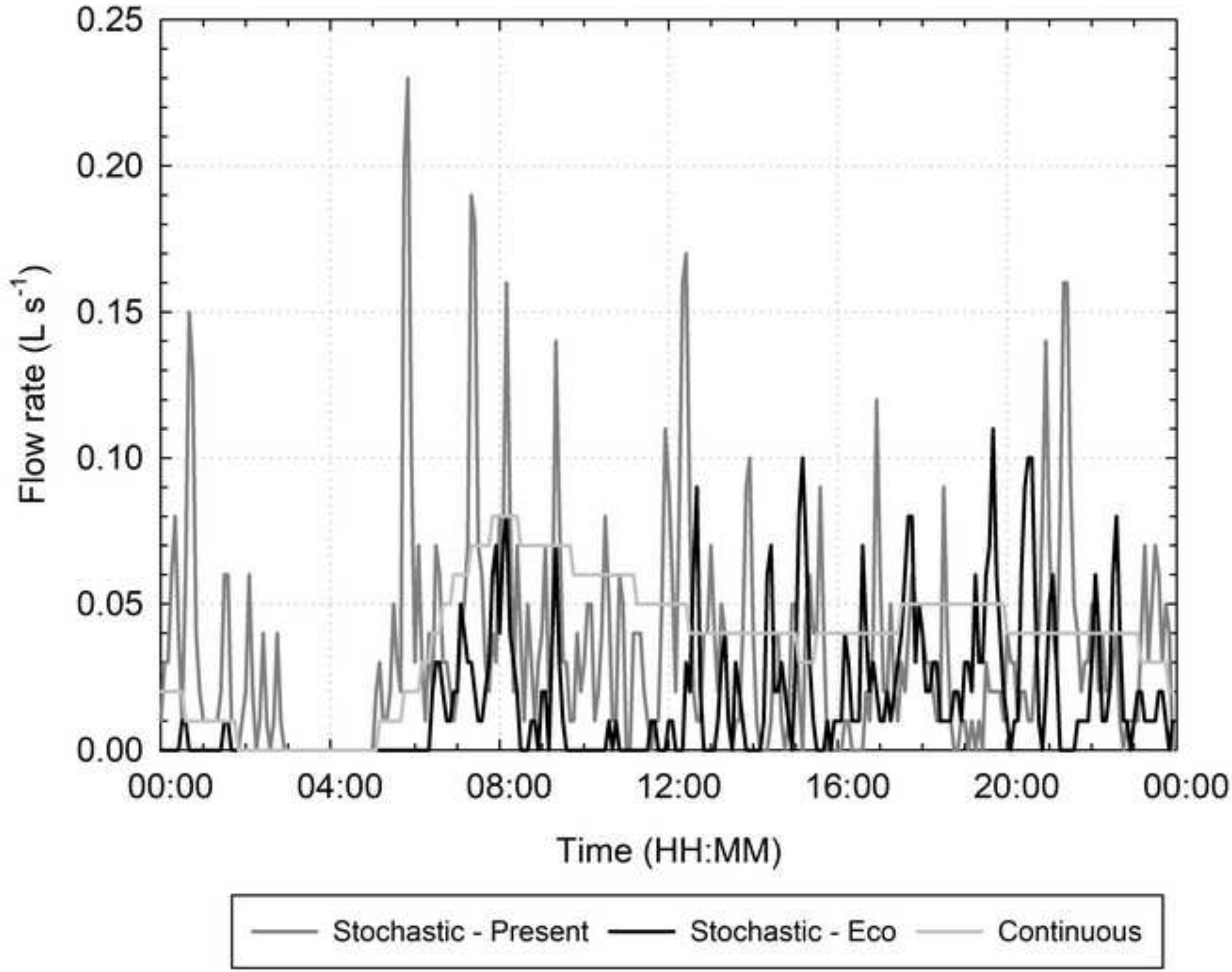


Figure 8

ACCEPTED MANUSCRIPT



ACCEPTED MANUSCRIPT

Table 1: Outline of appliance usage in SIMDEUM® scenarios

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

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 2: Differences in household occupancy between SIMDEUM® average and the case study

	One Person Households	Two person households	Family Households
SIMDEUM® Default	34%	30%	36%
Studied Catchment	26%	43%	32%

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Table 3: Analysis of stagnation in sewers as a result of changes in water use

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

ACCEPTED MANUSCRIPT

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

ACCEPTED MANUSCRIPT

ACCEPTED MANUSCRIPT

Highlights - *Developing a Stochastic Sewer Model to Support Sewer Design under Water Conservation Measures*

- Stochastic sewer model will help understand effects of water conservation
- Increased modelling accuracy compared to traditional continuous sewer model
- Low water use dramatically reduces daytime sewer flow, evening flow remains similar
- Capability to study appliance specific changes in wastewater flow and concentration
- Hydraulic model will be extended to include sewer water quality

ACCEPTED MANUSCRIPT