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Industrial Electrical Engineering and Automation

Household Wastewater Generation Model

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1 Introduction

This is an internal report in the research project Sustainability Analysis of Wastewater (WW) Heat Recovery (WWHR) – Hållbarhetsanalys av värmeåtervinning ur avloppsvatten (HÅVA), in Swedish – coordinated by the Division of Industrial Electrical Engineering and Automation at Lund University, Lund, Sweden. Key partners in the project are RISE Research Institutes of Sweden, the wastewater utilities VA Syd, Tekniska Verken in Linköping and Käppalaförbundet, and the real estate company Stångåstaden.

In the project a system-wide sustainability analysis will be performed using process models. The model will include components from the origin of domestic wastewater in buildings through WWHR units and sewers to the impact of temperature changes on the wastewater treatment plant (WWTP). The literature review on WWHR identified wastewater characteristics as a key variable for the model (Arnell et al., 2017). This document contains a description of a stochastic model for generating wastewater from households over the course of one day, which was calibrated based on measurements from a case study in Linköping, Sweden, and validated with literature data.

2 Model description

2.1 General description

The model is based on models developed in the Netherlands (Blokker et al., 2010) and Austria (Sitzenfrei et al., 2017), and is derived from water use statistics for different end use types in households. These include:

- Shower;
- Bathtub;
- WC (divided into two types, see Section 2.3.4);
- Dishwasher;
- Washing machine;
- Taps.

The general structure follows that of the model presented by Sitzenfrei et al. (2017) and is described below. Since this model is intended to describe water that ends up as wastewater, only water that is collected in the sewer system is included in the model (meaning that for example water used for irrigation is not included).

For each end use type, a behavioral diurnal use pattern describes the probability of use over the course of a day. This pattern depends on the time during which each individual is at home, and thus differs between work days and weekend days. Some variation between individual work days and weekend days are also apparent, as can be seen in Bagge et al. (2012), but for this work the division into separate aggregated patterns for work days and weekend days is deemed sufficiently accurate. The model therefore includes two separate diurnal use pattern curves, one for work days and one for weekend days, for each end use type stated above (with a few exceptions, as described in the following).

For each end use type a daily frequency of use is defined. For the end use types shower, bathtub, dishwasher and washing machine, this frequency of use is on average below 1 use/day, and is therefore expressed as a probability of use (0 < value < 1). For WC and tap use, which are normally used several times per day, a set number of use events per person and day is defined.

The amount wastewater that is generated during each use event is described by two probability functions, one for wastewater flow [$L.min^{-1}$] and one for duration of flow [min] (equivalent to the time during which the wastewater is drained), for each end use type. Both of these are assumed to be normally distributed, according to Sitzenfrei et al. (2017), and are thus described by a mean value (μ) and a standard deviation value (σ). During each use event, a value is randomly drawn from each distribution to describe the volume of wastewater that is generated for the specific event. For both distributions an interval is specified in which the flow and duration is allowed to vary during the event.

The wastewater temperature at each use event is, like the flow and duration, described by a normally distributed probability function (one for each end use type). During each use event, a random temperature is drawn from the distribution and equals the generated wastewater temperature for the volume of water that is generated at the event. An interval for which the temperature is allowed to vary is defined for each end use type.

A summary of the used (calibrated) model parameters is presented in Table 1, while the intervals for temperature, flow and duration are presented in Table 2

Table 1. Wastewater generation model parameters.

End use type	Volume generated	Frequency of use	μ_T	σ_T	μ_Q	σ_Q	μ_D	σ_D
-	$L.person^{-1}.d^{-1}$	$person^{-1}.d^{-1}$	°C	°C	$L.min^{-1}$	$L.min^{-1}$	min	min
Shower	80.6	0.7	37	0.7	12	0.9	9.6	1.0
Bathtub	2.3	0.03	37	0.7	10.5	0.5	7.4	0.6
WC_1	30	5	T_{cw}^*	1.0	6.0	0.3	1.0	0.15
WC_2	6	1	T_{cw}^*	1.0	6.0	0.3	1.0	0.15
Washing machine	10.0	0.2	45	1.5	8.9	0.6	5.6	0.3
Dishwasher	4.2	0.29	40	5.0	9.0	0.7	1.6	0.15
Taps	52.5	25	20	5	3.0	0.15	0.7	0.14

* T_{CW} = cold tap water temperature (model input parameter)

Table 2. Intervals for temperature, flow and duration for each end use type.

End use type	Temperature interval		Flow interval		Duration interval	
	T_{min}	T_{max}	Q_{min}	Q_{max}	D_{min}	D_{max}
	°C	°C	$L.min^{-1}$	$L.min^{-1}$	min	min
Shower	35	40	8	15	4.0	14.1
Bathtub	35	40	8	12	5	9.2
WC_1	T_{cw} -1	T_{cw} +1	3	9	0.5	1.5
WC_2	T_{cw} -1	T_{cw} +1	3	9	0.5	1.5
Washing machine	30	60	7	11	4	7
Dishwasher	30	80	7	12	1.2	2.1
Taps	T_{cw}	45	2	4	0.3	1.2

2.2 Time of use

Initial time of use patterns are derived from two separate sources:

- Flow data collected during a study in Sweden where flow meters where installed on individual taps in 10 different households for a total of 3 weeks (Swedish Energy Agency, 2008). This data is used to derive diurnal use patterns for all end use types except dishwasher and washing machine, divided in work day and weekend,
- A German study where dishwasher and washing machine use in several European countries (among them Sweden) has been studied, based on a EU survey (Stamminger & Schmitz, 2017). This data is used to derive diurnal use patterns for dishwasher and washing machine, but no distinction between work day and weekend use can be made.

For one end use type (bathtub), no data is available in the sources above. Data from Sitzenfrei et al. (2017) is therefore used. Due to the few numbers of households which the data is based on, calibration of the values is needed to obtain a more generally valid model. The data is therefore used as a starting point for calibration.

To describe the probability of occurrence for each usage event during the course of a day, a probability density function (PDF) is used. This is described mathematically according to Equation 1 (Wärff et al., 2020). The PDF is constructed by combining four normal distributions (k = 4), each with a mean value ($\mu_{h,k}$) and standard deviation ($\sigma_{h,k}$), where the index h indicates hour of the day. This methodology is consistent with the model presented by Sitzenfrei et al. (2017), although in that case three normal distributions where used to form the PDF. The (calibrated) values for each normal distribution are given in Table 3. The mean values should be interpreted as the time of day where the peak of each bell curve given by the single normal distribution occurs, while the standard deviation describes the spread of the bell curve (larger $\sigma_{h,k}$ = wider curve with lower magnitude of peak, opposite for smaller values). Negative values mean that the peak occur outside of the 24 hours to obtain the correct nighttime probability. When the 4 normal distributions are combined the PDF for the probability of use for each day is obtained.

$$f(x) = \frac{\sum_{n=1}^{k} \frac{1}{\sigma_{h,n}\sqrt{2\pi}} e^{-(x-\mu_{h,n})^2/(2\sigma_{h,n}^2)}}{\int_{X=0}^{24} \left(\sum_{n=1}^{k} \frac{1}{\sigma_{h,n}\sqrt{2\pi}} e^{-(X-\mu_{h,n})^2/(2\sigma_{h,n}^2)} \right)} ; 0 \leq x \leq 24 \quad (1)$$

where *f(x)*: probability function; *x*: time of day [h]; *X*: vector with all time of day values [h] for 24 hours, used to norm the PDF.

Table 3. Probability function values for the wastewater generation model (calibrated values).

End use type	Work day		Weekend	
	$\mu_{h,k}$, k=1/2/3/4	$\sigma_{h,k}$, k=1/2/3/4	$\mu_{h,k}$, k=1/2/3/4	$\sigma_{h,k}$, k=1/2/3/4
Shower	-3.3/8.6/14.0/20.5	2.5/2.4/4.0/2.7	-3.5/11.1/13.0/19.5	2.0/2.2/4.0/3.0
Bathtub	-/10.0/14.0/20.0	-/2.4/3/2.2	-/10.0/14.0/20.0	-/2.4/3/2.2
WC	-3.0/7.8/15.0/20.7	3.5/1.8/4.0/2.8	-3.0/10.6/17.0/20.3	3.2/2.0/3.5/3.6
Washing-machine*	-	-	-	-
Dishwasher*	-	-	-	-
Taps	-4.0/8.5/14.0/20.5	3.2/1.7/3.5/2.4	-3.8/10.4/14.0/20.0	2.8/2.5/3.0/3.1

* Probability density function not described by normal distributions, instead calculated from Stamminger & Schmitz (2017)

2.2.1 Flow data from Swedish Energy Agency (2008)

The flow data was collected from 10 households (denoted A-J), 4 of them (A-D) apartment multi household buildings and the rest of them (E-J) one household houses. The data has a one-minute temporal resolution and has been recorded for several appliances in the households. The end use type that was used for flow measurements differed some between the different households. The ones that were measured for all households include:

- Shower;
- Kitchen (one measurement including both tap water use and dishwasher use, for the households that have a dishwasher (7 of 10));
- Wash basin (tap water use in bathroom). Some households have two.

WC use was only measured in two households. 7 of the 10 households have a washing machine, but flow from this has only been measured in two of the households. In 3 of the remaining households, flow in the laundry room has been measured.

The data was analysed for use patterns. A single use was defined as any time that flow data greater than zero was detected, when the previous data value in the time series was zero (or if the data point is the first point in the time series). The time of use for each individual use was recorded and the date that the recording was made was used to determine if the use occurred on a work day or weekend. This was performed separately for each household. The resulting dataset was then normalized to the number of inhabitants in the household, as well as balanced for missing data. This balancing was done by calculating the number of work days and weekend days for each data set and dividing this with a reference (the expected number of days during a three week period, 6 weekend days or 15 work days for the weekend and work day data sets respectively), according to Equation 2:

$$\text{dataset}_{\text{new}} = \text{dataset}_{\text{old}} * \frac{\text{reference days}}{\text{number of days}} \tag{2}$$

A smoothing of the curve was performed by calculating the average over 6 data points before and after each data point (in total an average over 13 x 15 min = 195 min). The cumulative density function (CDF) for time of use was calculated based on this smoothed curve. Besides providing smoothing of the curve, this also attenuates uncertainty regarding the probability of time of use because of the small number of households that have been measured and the short time measured (3 weeks). A comparison between the data before and after smoothing can be seen in Figure 1.

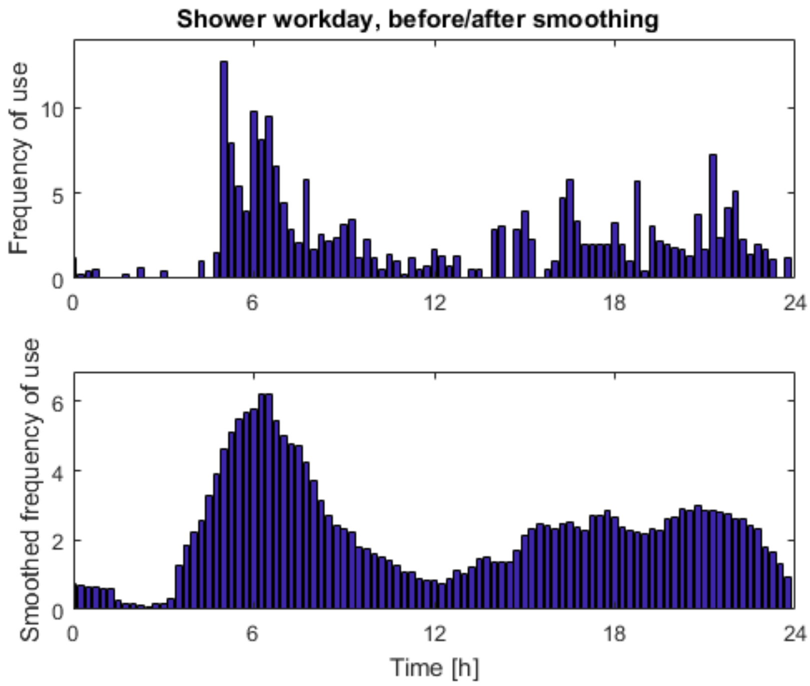

Figure 1. Shower use (work day) data before (upper) and after (lower) smoothing.

The diurnal patterns for shower use were straight forward to obtain since the measured data could be used directly. For the other end use types though, some data management and assumptions had to be made.

The tap water use is considered as one end use type in the model, and a distinction between tap water use in the kitchen or in the wash basin is not made. The diurnal use pattern was therefore constructed by adding the diurnal patterns obtained from measurements in the kitchens and wash basins together as one.

The flow from WC use was only measured in two of the households, I and J. WC use therefore needs to be obtained in another way for households A-H. It is reasonable to assume that the wash basin often is used for washing of hands in close proximity to WC use, so to investigate this the WC use and wash basin use for households J and I were calculated. For both work day and weekend use, a linear (Equation 3) and an exponential (Equation 4) model fit for correlation between the variables were tested.

$$y = k_{lin} * x + c_{lin} \tag{3}$$

$$y = c_{exp} * \left(1 - e^{-k_{exp} * x}\right) \tag{4}$$

where $k_{lin/exp}$: model coefficient for the linear/exponential models;
$c_{lin/exp}$: model constant for the linear/exponential models;
x: smoothed, normed use of wash basin;
y: smoothed, normed use of WC.

The data show a reasonable correlation between wash basin use and WC use for both workday and weekend use. This can be seen in Figure 2 (work days) and Figure 3 (weekend days), with correlation between the patterns for use (upper graph in each figure), as well as the data itself and the WC data generated from the linear- and exponential models (lower graph in each figure). The obtained parameters with confidence intervals and the R^2-value are presented in Table 4. It was therefore assumed that this correlation holds true for the remaining households as well, and the exponential equation in Figure 2 was used to calculate WC use patterns in households A-H.

Table 4. Calculated coefficients for correlation between wash basin and WC use (with 95% confidence intervals).

	k	*c*	R^2
Work day, linear	0.8902 ± 0.058	0.0011 ± 0.00078	0.90
Work day, exponential	42.4868 ± 12.94	0.0330 ± 0.0083	0.93
Weekend, linear	0.8845 ± 0.052	0.0012 ± 0.00062	0.92
Weekend, exponential	41.0793 ± 17.49	0.0313 ± 0.011	0.92

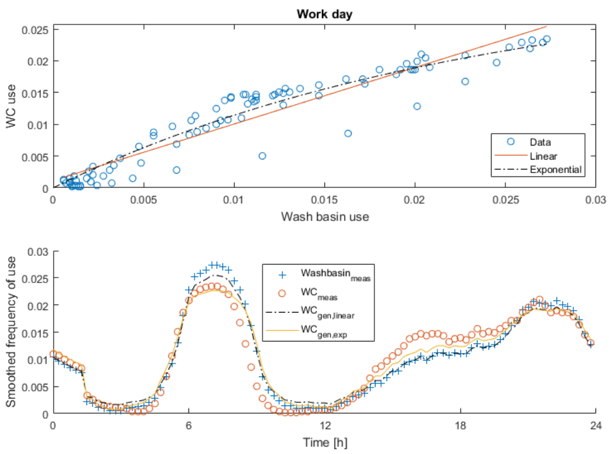

Figure 2. Wash basin and WC use during work days in household I and J, with correlation between the variables.

The model parameters in Equation 1 was then used to fit the function to the data derived in the PDFs to obtain an initial fit of the model to data. The model is able to accurately fit the use patterns (see Figure 4), which validates the choice of the simple model with four normal distributions to describe the use patterns. As the patterns are derived from a low number of households, it is unlikely that the initial fit will be able to describe larger aggregation of households with different habits without calibration. This proved to be the case for a case study in Linköping where the model was calibrated to successfully describe the wastewater generation (Wärff et al., 2020).

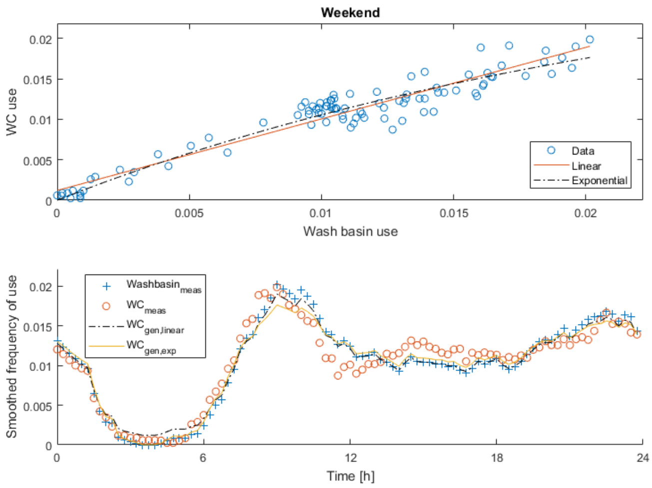

Figure 3. Wash basin and WC use during weekend days in household I and J, with correlation between the variables.

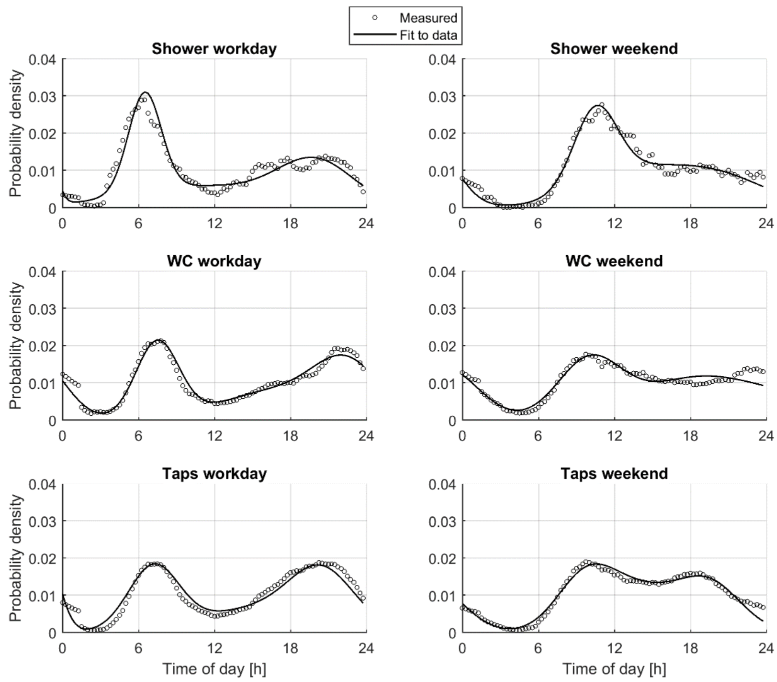

Figure 4. Measured time of use PDF data and initial model fit to measurements.

No separate flow measurement data from bathtub use was available. Therefore, the pattern given in Sitzenfrei et al. (2017) was used for both work day and weekend. Since separate dishwasher did not exist and washing machine flow was only measured in two households, PDFs for these appliances were obtained separately from EU survey data (see below). Those patterns do not divide into work day or weekend use, only a single use pattern for each end use type is available. The overall impact of these assumptions on the model results are deemed low as the average daily volume originating from these is low (<9 percent of the total daily volume). It should, however, be taken into consideration if one needs to investigate specific questions regarding these appliances.

2.2.2 EU survey data from Stamminger & Schmitz (2017)

Flow to dishwashers and washing machines were not individually measured in the study by the Swedish Energy Agency (2008). The diurnal use patterns for these were therefore derived from a study where a survey has been made on a large number of residents in Sweden (Stamminger & Schmitz, 2017), comprising 294 persons of data for washing machines and 296 persons for dishwashers. The PDFs for dishwashers and washing machines were calculated from the data available in Stamminger & Schmitz (2017), with the same methodology as given in the same paper. The results were also compared to the calculated diurnal power demand given in the paper (which is based on the calculated diurnal use patterns) as a validity check. The results seem reasonable and are shown in Figure 5. In the calibration phase, night-time use of these appliances was deemed very low for the case study and set to zero (resulting PDFs not shown).

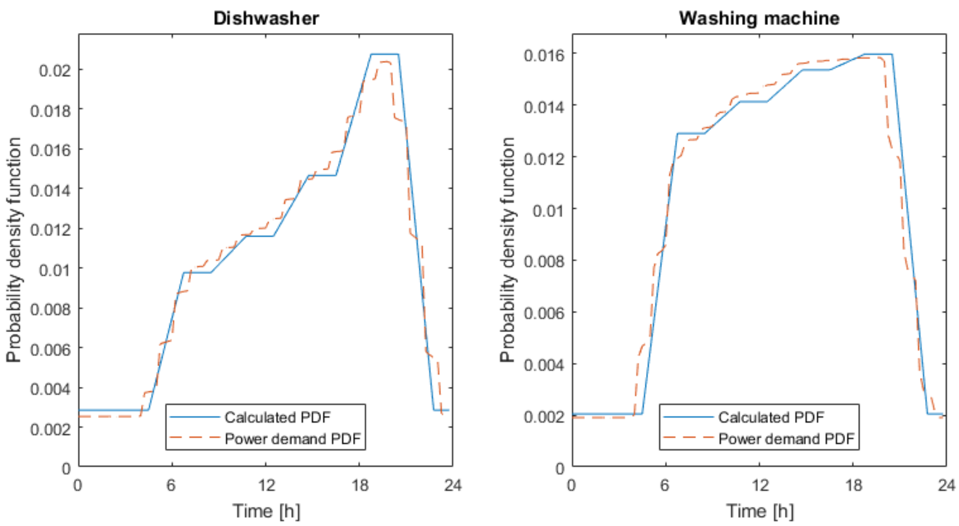

Figure 5. Comparison of calculated time of use probability density function (PDF) and data for power demand diurnal PDF, with data from Stamminger & Schmitz (2017).

2.3 Frequency of use, flow and duration of use

Several sources are used for calculation of the daily frequency of use per person for different end use types. Some sources contain data based on interviews or surveys, where the data is presented in the format shown in Table 5, with bathtub data used as an example. This data has to be re-calculated to obtain the relevant unit of times per person and day. For these calculations, the product sum of the frequency of use and the fraction of responses is used to calculate the overall frequency of use per person and day.

For the values where a range is given, as for example 4 – 6 times per household and week, the mean value is used. For the values where a lower limit is given, as for example >2 times per household and day, the limit value is used. For the values where an upper limit is given, as for example <1 time per household and week, half of the limit value is used for the calculation.

For some sources the unit used is per household and day (as in the example in Table 5). In the sources where the number of inhabitants in the households in the specific study is given, this number is used to convert the unit to be based per person instead. For the larger studies where the number of inhabitants in the household are not given, the Swedish mean value of 2.2 persons/household (Statistics Sweden (SCB), 2018) is used.

Table 5. Example of data representation from literature regarding frequency of use for bathtub (Carlsson-Kanyama et al., 2004).

Frequency of use	Fraction of responses [-]
>2 [times/household,day]	0.01
1 [time/household,day]	0.036
4 – 6 [times/household,week]	0.10
1 – 3 [times/household,week]	0.27
<1 [times/household,week]	0.58

Note that the overall water use can vary significantly between different types of households, with the average daily water consumption per person being higher for multi-family buildings compared to single family buildings (Swedish Energy Agency, 2009), as well as different areas (Bagge et al., 2012; Swedish Energy Agency, 2009). The statistics presented below are the results from a literature review for Swedish conditions, but as these types of statistics are scarce the most uncertain ones (e.g. shower and tap water use) are used as calibration parameters. The values presented in Table 1 and Table 2 have been calibrated for flow and temperature and validated for the flow pattern for large areas and can be used (with caution) for other areas.

2.3.1 Overall use

For the overall water use the Swedish Water and Wastewater Association (2017) reports a daily average of 140 L.person^{-1}.d^{-1}. The distribution in different end use types is shown in Figure 6.

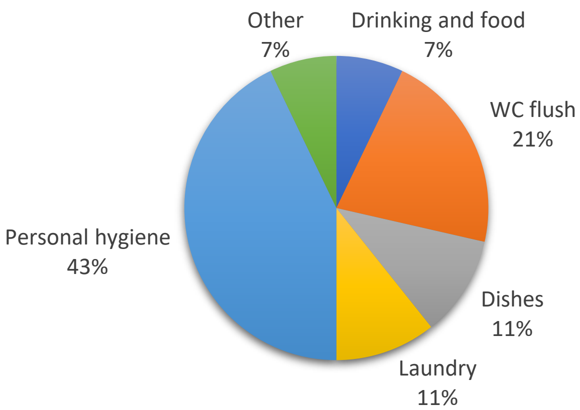

Figure 6. Water use distribution in Sweden according to the Swedish Water and Wastewater Association (2017).

The total water consumption according to the statistics presented below amounts to 178 L.person^{-1}.d^{-1}. This is higher than the value specified by the Swedish Water and Wastewater Association (2017), but in a reasonable range for multi-family buildings. For example, Mahmoudi (2017) found that the specific water consumption in Gotheburg, Sweden, in 2017 varied between 166 – 177.4 L.person^{-1}.d^{-1} when measured in different areas of the city. This number only included registered tenants older than 16 years, since children <16 years are not included in the public information regarding tenants. When the approximate number of children was calculated, the corresponding water consumption was 134.7 – 147.9 L.person^{-1}.d^{-1}. A representative value may lie between these intervals. Swedish Energy Agency

(2009) found that the mean water consumption in apartment buildings were 184 $L.person^{-1}.d^{-1}$ while the consumption in single household buildings were 130 $L.person^{-1}.d^{-1}$. During the measurement period in an apartment block in Linköping for the case study for which the model is calibrated, the water consumption was 184 $L.person^{-1}.d^{-1}$.

2.3.2 Shower

Data of frequency of use of showers in Sweden is scarce, although a few sources have been found. DN (2010) reports an average use of shower or bathtub of 0.73 $person^{-1}.d^{-1}$, based on an opinion poll of 1000 persons. This conforms very well to the numbers reported in Sitzenfrei et al. (2017) of a shower frequency of use of 0.7 $person^{-1}.d^{-1}$ and a bathtub use of 0.03 $person^{-1}.d^{-1}$. A frequency of 0.74 was calculated from data in Li & Flyman (2013), which also is close to the value from DN (2010). Since the value from DN (2010) is based on a larger data set, and is equivalent to the value from Sitzenfrei et al. (2017), the value 0.7 $person^{-1}.d^{-1}$ is used.

The average shower duration is calculated to 10.6 minutes, based on data from Li & Flyman (2013). This value is deemed a major uncertainty and thus targeted as a calibration parameter.

According to Swedish design guidelines (BFS 2011:6, 2011), a normal shower flow is 0.2 $L.s^{-1}$ (corresponding to 12 $L.min^{-1}$). With the shower duration above, the total average shower water use per person and day then equals 89.1 L.

2.3.3 Bathtub

The bathtub frequency of use was calculated to 0.03 according to the methodology presented in Section 2.3.2, which is equivalent to the value presented by Sitzenfrei et al. (2017). Based on data collected from Carlsson-Kanyama et al. (2004), a mean bathtub frequency of use of 0.093 $person^{-1}.d^{-1}$ is calculated. This frequency is initially deemed too high, and the value of 0.03 is used.

No other specific data for bathtub use under Swedish conditions has been found, and the relevant parameters are therefore assumed to be equal to the values provided by Sitzenfrei et al. (2017). This means a mean duration of 7.4 minutes and a mean flow of 10.5 $L.min^{-1}$. This duration corresponds to the draining time of the bathtub, not the actual bathing time. In terms of volume, this corresponds to a bathing volume of 77.7 L, while most bathtubs contain a volume of 200 – 300 L. To obtain more realistic results, the total volume (duration and/or flow parameters) in the model could be increased to 250 L (for example with a duration of 10 minutes and a flow of 25 $L.min^{-1}$), while changing the frequency of use to 0.0092 $person^{-1}.d^{-1}$. The total average volume produced per person and day would then remain close to the value presented here. For Swedish conditions this would be a reasonable assumption as the use of bathtubs in Sweden today is not very common.

2.3.4 WC

For added model flexibility, the WC use is divided into two separate events:

1. Urination only (denoted WC_1);
2. Urination and defecation (denoted WC_2).

In this way, changes in use (as in differences in flush volume and implementation of urine diverting toilets) can be easily implemented. It is assumed that urination always takes place at a defecation event.

The total average toilet frequency of use is presented by Jönsson et al. (2005), where 8.3 and 9.5 $person^{-1}.d^{-1}$ are given for two different housing areas, where the latter value is assumed to represent average Swedish conditions. These values, however, is not representative for the number of flushes used when at home. Instead, the original measurements in the households have been linearly extrapolated with the total time spent at home to obtain the number of flushes over 24 hours. The average time at home for the two housing areas were 13.9 and 15.9 hours respectively (Jönsson et al., 1998), meaning that the average number of flushes when at home were 4.8 and 6.3 $flushes.person^{-1}.d^{-1}$ (where the latter value was deemed representative of average Swedish conditions). Thus, the total number of flushes is assumed to be 6 per person and day. This is also equal to the number given by Sitzenfrei et al. (2017) for Austrian conditions. Out of these, urination and defecation at the same event is assumed to occur 1 $person^{-1}.d^{-1}$, based on the average number of defecations per person and day presented by Rose et al. (2015) as well as the 1-2 times per person and day cited by Jönsson et al. (2005) (original reference not found). The remaining 5 toilet use events are assumed to occur with urination only.

In this version of the model a toilet with one flushing volume is assumed. If needed, the model can easily be modified with a lower volume flush option for use when only urination is considered. As flushing occurs quickly, duration is assumed to 1 minute. In reality, it is only a few seconds, but as the model aggregates values in 15-minute intervals it will not make any difference for the results. For this work, a flush volume of 6 L is assumed, which means that the flow is equal to 6 $L.min^{-1}$ per WC use.

2.3.5 Washing machine

The frequency of use is calculated from data in Stamminger & Schmitz (2017) to 0.20 $person^{-1}.d^{-1}$, from data in Li & Flyman (2013) to 0.21 $person^{-1}.d^{-1}$ and from data in Carlsson-Kanyama et al. (2004) to 0.35. The value 0.20 is therefore deemed reasonable.

The flow at each event is assumed to equal the value given in Sitzenfrei et al. (2017), of 8.9 $L.min^{-1}$. With a laundry water use of 15.4 $L.person^{-1}.d^{-1}$ (Swedish Water and Wastewater Association, 2017) and the frequency of use given above, a total water volume of 77 $L.use^{-1}$ is found. This value is believed to be too high, as several sources point to a water consumption of about 50 $L.use^{-1}$ in washing machines to be more reasonable (between 40-57 $L.use^{-1}$ with the energy saving program, according to Swedish Energy Agency (2017b), although the water use in alternative, non-energy saving program varied between 65-99 $L.use^{-1}$). An average water use of 50 $L.use^{-1}$ is therefore assumed, which gives a duration of 5.6 minutes. The total laundry water use with 10 $L.person^{-1}.d^{-1}$ is therefore 35 percent lower than the one specified in the Swedish Water and Wastewater Association (2017).

2.3.6 Dishwasher

The frequency of use is calculated from data in Stamminger & Schmitz (2017) to 0.29 $person^{-1}.d^{-1}$.

The volume per use for dishwashers can vary, but in a recent study of several different dishwashers the water use varied between 8 – 18 $L.use^{-1}$ (Swedish Energy Agency, 2017a). The flow (9 $L.min^{-1}$) and duration (1.6 min) given by Sitzenfrei et al. (2017) gives a volume of 14.4 $L.use^{-1}$, which is deemed reasonable for Swedish conditions as well.

2.3.7 Taps

As no specific data for Swedish conditions have been found, the initial frequency of use, flow and duration for tap water use is assumed to equal the number given in Sitzenfrei et al. (2017) (corresponding to 21 $person^{-1}.d^{-1}$, 2.5 $L.min^{-1}$ and 0.7 $min.use^{-1}$). Due to the lack of statistics these values are used as initial values and then considered calibration parameters.

2.4 Temperature

The temperature model is constructed identically to the model by Sitzenfrei et al. (2017), meaning that the temperature at each water use occasion is assumed normally distributed with a mean value and standard deviation. An interval is specified for which the stochastic temperature value is allowed to vary. Temperature values for all end use types are also assumed to equal the values specified in Sitzenfrei et al. (2017), with the exception of the values stated below.

The WC mean value that has been replaced with the cold tap water temperature. The cold tap water temperature is used an input parameter to the model, provided as a daily value. A dynamic input with variable temperature over the week and seasons is possible. However, it is assumed constant for each day.

Stamminger & Schmitz (2017) specifies an average washing machine water temperature of 45.0 °C, which is therefore used as the mean model temperature. The span is set to range between 30 °C and 60°C, which are normal washing temperatures.

2.4.1 Temperature loss in building

The wastewater loses some of the heat during the transport from the point of use to the sewer outside the building, and this needs to be accounted for in the model. Sitzenfrei et al. (2017) assumed the temperature loss from the point of use to the sewer to equal Equation 5:

$$\Delta T = \min\left(10^{-10} * T_i^{6.673}, 7.5\right) \tag{5}$$

where T_i [°C] is utilization temperature during each use event and 7.5 is a maximum ΔT.

This was based on measurements of the change in shower water temperature from the shower head to the shower drain by Wong et al. (2010). For this model, the same assumption as used in the model by Sitzenfrei et al. (2017) is used for all end use types. This is a topic that would benefit from more research with measurements to develop better models for the heat loss within buildings.

2.5 Pollutants

Pollutants are added as a fixed load [g] per use event for each of the different end use types (Table 6), and is therefore not a stochastic process. Variations in pollutant concentration is caused by variations in water flow and the number of use events. Five different pollutant variables are considered:

- Soluble COD (COD_{sol});
- Particulate COD (COD_{part});
- Ammonium nitrogen (NH_4-N);
- Total Kjeldahl nitrogen (TKN);
- Total phosphorus (TP).

Further fractionation into activated sludge model (e.g. ASM1/2d/3) state variables is performed with a model block in the sewer network model, before reaching an eventual wastewater treatment plant model.

The pollutant loads from each end use type are summarized in Table 7, while the calculations and assumptions behind the values are presented below. Please note that the pollutant model has yet to be calibrated/validated with pollutant data from a wastewater stream.

Table 6. Assumed total loads per person and day (Balmér, 2018; Jönsson et al., 2005).

COD [g O_2.person^{-1}.d^{-1}]	NH_4-N [g N.person^{-1}.d^{-1}]	TKN [g N.person^{-1}.d^{-1}]	TP [g P.person^{-1}.d^{-1}]
120.6	10.8	13.67	1.56

Table 7. Pollutant load from each use event from each end use type.

End use type	COD_{sol} [g O_2.use^{-1}]	COD_{part} [g O_2.use^{-1}]	NH_4-N [g N.use^{-1}]	TKN [g N.use^{-1}]	TP [g P.use^{-1}]
Shower	4.28	4.38	0.057	0.36	0.074
Bathtub	3.77	1.48	0.035	0.22	0.045
WC_1 (urination only)	1.32	0.10	1.72	1.83	0.15
WC_2 (urination and defecation)	6.92	58.6	2.02	3.33	0.65
Washing machine	52.1	17.9	0.22	1.35	0.10
Dishwasher	12.3	16.8	0.12	1.08	0.047
Taps	0.47	0.45	0.003	0.017	0.004

2.5.1 COD

The total COD load per person and day is assumed to be 120.6 g O_2.person^{-1}.d^{-1}, according to Jönsson et al. (2005). The load from each end use types are calculated from a range of sources, as described below, with the compilation from many studies presented by Friedler (2004) being a major source.

Swedish Environmental Protection Agency (1995) assigns a total COD value (COD_t, soluble + particulate) of 7 g.person^{-1}.d^{-1} originating from showers and bathtubs. With the measured loads of total COD from Almeida (1999) and Friedler (2004), and the water use statistics in the calibrated model, the division of COD between shower and bathtub use can be made (97.5 and 97.2 percent of the daily load originates from showers based on the two references). The division between soluble and particulate COD is assumed equal to the ratio calculated from values obtained by Friedler (2004), with COD_{sol}/COD_t = 0.49 for shower and 0.72 for bathtub.

The WC COD load is based on values provided in Jönsson et al. (2005), and separated into two types of events (urination only and urination + defecation). The load from urination is divided over the total number of toilet events per day, while the load from defecation only is included in the urination + defecation event.

The COD_t load from the use of washing machines is assumed to be 14 g O_2.person^{-1}.d^{-1} (Swedish Environmental Protection Agency, 1995). With a frequency of use of 0.2 times.person^{-1}.d^{-1}, a value of 70 g COD_t/use is obtained. The division between soluble and particulate COD is assumed equal to the ratio calculated from values obtained by Friedler (2004), with COD_{sol}/COD_t = 0.74.

The COD load from the use of dishwashers is calculated from and assumed equal to values found by Friedler (2004).

The COD load originating from events with tap water use, such as manual dish washing and washing of hands etc., is assumed to contain the remainder of the COD to reach a total COD load as stated above. The fraction of COD_{sol}/COD_t = 0.52 is calculated from the average of wash basin and kitchen fractions in Friedler (2004). This load is split over the number of use events for tap water.

2.5.2 Nitrogen

The total Kjeldahl nitrogen load per person and day is assumed to be 13.67 g N $person^{-1}.d^{-1}$ while the ammonium nitrogen load is assumed to be 10.8 g $N.person^{-1}.d^{-1}$, according to Jönsson et al. (2005). The load from each end use types are calculated from a range of sources, as described below.

The nitrogen load from shower and bathtub use is based on the total nitrogen measurements by Swedish Environmental Protection Agency (1995) of 0.29 g $N.person^{-1}.d^{-1}$. This is assumed to equal the TKN load. The division between shower and bathtub load is performed in the same way as for the COD calculations. The NH_4-N load is calculated assuming the NH_4-N/TKN ratio for greywater given in Jönsson et al. (2005) of 0.16 and is valid for shower and bathtub water as well.

The WC nitrogen load is calculated in the same way as for COD, with values for TKN and NH_4-N originating from Jönsson et al. (2005).

The nitrogen load from washing machines is calculated in the same way as for COD, with the total nitrogen load from washing machines assumed as 0.27 g $N.person^{-1}.d^{-1}$ (Swedish Environmental Protection Agency, 1995) and this value assumed to represent TKN. The NH_4-N load is calculated with the NH_4-N/TKN ratio for greywater given in Jönsson et al. (2005) of 0.16.

The NH_4-N load from dishwasher use is calculated from the measurements in Friedler (2004). The TKN load is then calculated from the NH_4-N/TKN ratio for greywater from Jönsson et al. (2005) of 0.16. This is also close to the NH_4-N/TN ratio of 0.11 from Siegrist (1976), as quoted by Eriksson (2002).

The nitrogen load from tap water use is calculated in the same way as for COD, and is thus used to obtain the total TKN and NH_4-N load per person and day given in Jönsson et al. (2005).

2.5.3 Phosphorus

The total phosphorus (TP) load per person and day is assumed to be 1.56 g $P.person^{-1}.d^{-1}$, according to Balmér (2018). The load from each end use types are calculated from a range of sources, as described below.

The TP load from shower and bathtub use is based on the measurements by Swedish Environmental Protection Agency (1995). The division between shower and bathtub load is performed in the same way as for the COD calculations.

The WC TP load is calculated in the same way as for COD, with values originating from Jönsson et al. (2005).

The TP load from washing machines has generally been high because of high amounts of phosphate in the washing detergent. In Sweden, however, the phosphorus content in washing detergent is regulated since 2008 and may not contain a TP concentration of above 0.2 percent by weight (SFS 2007:1304). Older measurements from Sweden and measurements from abroad are therefore likely overestimated when compared to today's conditions. Therefore, the TP load has to be calculated from the situation today. To calculate the P content per washing event, a washing detergent dose of 50 ml/wash was assumed (representing a typical dose for soft water conditions, which is valid for the majority of households in Sweden). The density of a detergent (Via Color) is given as 1.044 $g.ml^{-1}$. With an assumed maximum phosphorus content of 0.2 percent by weight, the TP load per wash equals 0.10 g P. It is assumed that no additional sources of phosphorus is included for washing.

The TP load from dishwasher use originates from organic waste and dishwasher detergent. In Sweden, like for washing detergent described above, the phosphorus content in dishwasher detergent is regulated since 2011 (SFS 2010:267). It not allowed to contain more than 0.5 percent P by weight. Older measurements in Sweden and measurements from abroad are therefore likely overestimated, as detergent with high phosphorus content was likely used in those studies. Therefore, the entire TP load from dishwashers in the model is assumed to originate from the detergent, with 0.005 g P.g $detergent^{-1}$. The detergent use is assumed to be 15.68 $g.use^{-1}$, calculated from an average dishwasher tablet weight from a manufacturer (Yes).

The TP load from tap water use is calculated in the same way as for COD, and is thus used to obtain the total TP load per person and day given in Balmér (2018).

3 Model calibration and validation

The model calibration procedure and case study are described in Wärff et al. (2020), but are also briefly introduced here. Initially, the model values used were based on the statistics presented in Section 2. For the probability distributions for time of use for each appliance, the initial fit to data presented in Section 2.2 was used as starting point. The model output was then compared to the measured values from Linköping and calibrated according to the procedure presented in Figure 7.

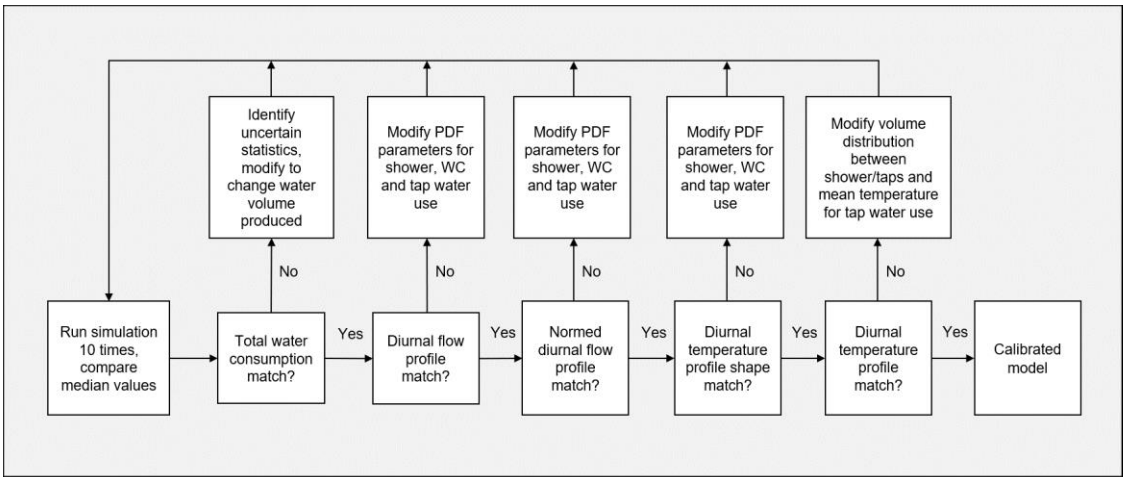

Figure 7. Model calibration procedure.

Calibration of the time of use PDFs were necessary to obtain a good fit of the model to the measured data, as was expected due to the low number of households used for the initial fit. The change was mainly needed for workday values, with the largest change needed for the morning peak of shower use. This was expected, as the data originate from few households where the daily routines for morning shower was relatively similar. From a larger sample size, larger variations in morning habits are expected. The measured data, initial model fit and calibrated model are shown in Figure 8.

The model is able to describe the measured wastewater flow and temperature well, as can be seen in Figure 9 and with the mean simulated and measured values for the period as shown in Table 8. In Table 8 a comparison of the fraction of hot water use in the case study as well as literature values from a multi-family building with similar total water use (Swedish Energy Agency, 2009) is also shown, with a close match between the model values and literature data. The model was validated with normed flow data from Nikell (1994) as well as unpublished data from measurements in Karlstad (described in Bagge et al. (2015) and Bagge et al. (2018)), as seen in Figure 10. Since the variations in total water use per person is substantial between these sources, the normed flow was considered better for validation than the absolute flows. Note that this therefore validates the general flow distribution over the day. For some data points, mainly during the weekend, the simulated median values do not appear within the confidence interval of the measurements. This is deemed to be at least in part to the low number of measurements (two days of measurements, meaning two data points per time step), which causes the large variations in the confidence intervals for the data points during the weekend. A force fit of the model to these data points would mean that the fit to validation data would deteriorate, therefore the presented fit is deemed the most reasonable.

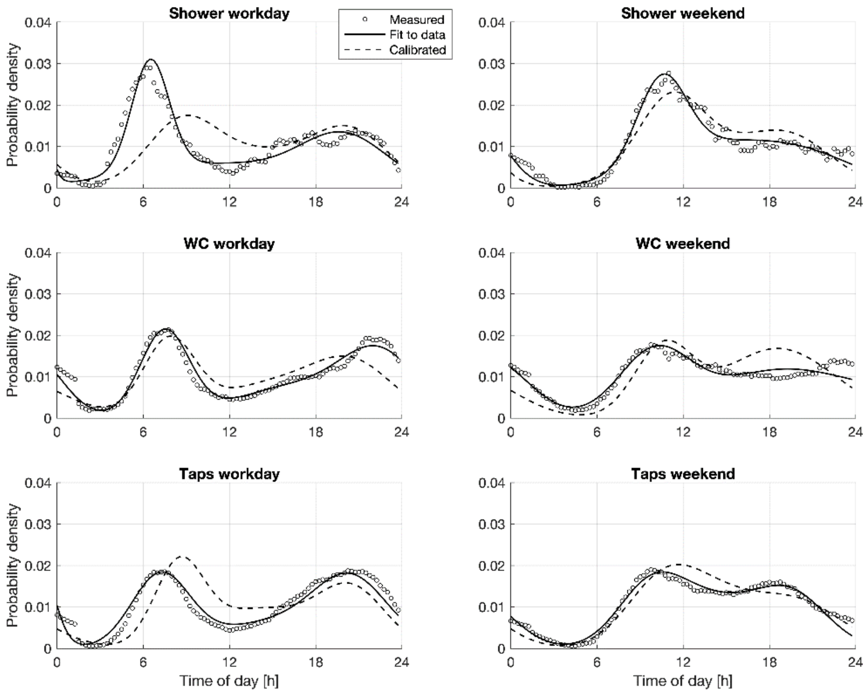

Figure 8. Measured data, initial model fit and calibrated model values for time of use PDFs.

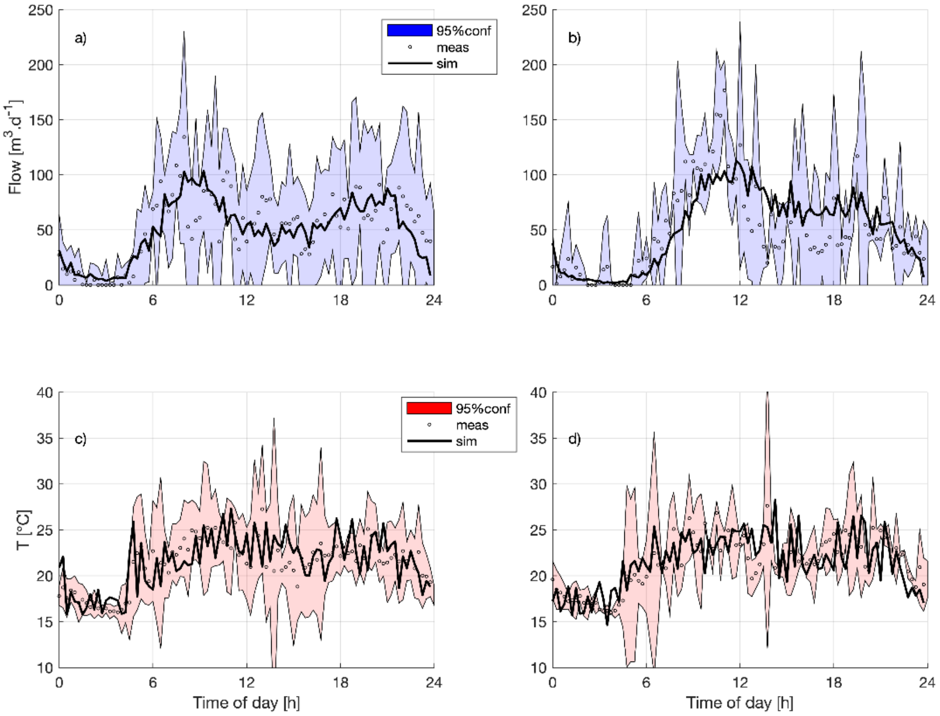

Figure 9. Measured and calibrated median work day (a) and weekend (b) flow and work day (c) and weekend (d) temperature values. Shaded areas indicate 95 percent confidence values of the measurements.

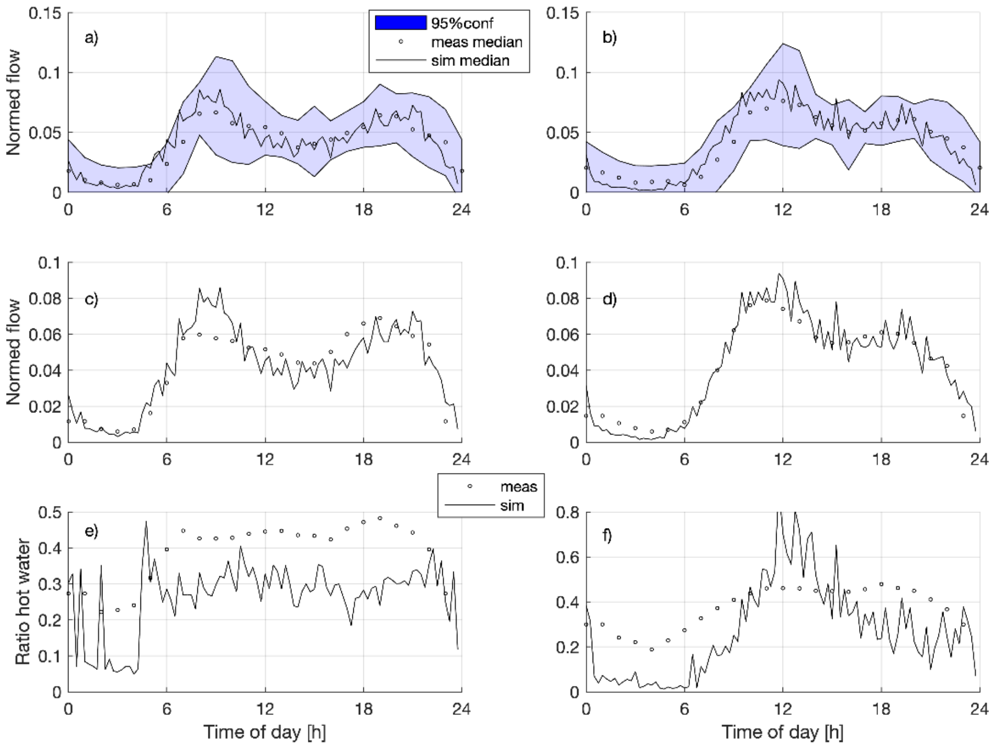

Figure 10. Normed simulated median flow compared to measured median values and 95 percent confidence intervals of the measurements form water demand curves from Nikell (1994) for work day (a) and weekend (b), as well as normed simulated median flow compared to normed measured median flow of household water (work day (c) and weekend (d)) and hot water fraction of total water consumption (work day (e) and weekend (f)) from measurements in Karlstad, Sweden.

Table 8. Mean water use during measurements and calibration of the model, compared to literature data from a multi-family building where the total water consumption was similar to the presented case (186 $L.person^{-1}.d^{-1}$).

Target	Unit	Reference value	Calibrated value	Reference
Total water use	$L.person^{-1}.d^{-1}$	184	184	Measured
	$m^3.d^{-1}$	51.8	51.3	Measured
Hot water use	$L.person^{-1}.d^{-1}$	58	55.6	Swedish Energy Agency (2009)
Hot water fraction	L_{hot}/L_{tot}	0.315	0.302	Swedish Energy Agency (2009)

4 Examples of model output

Below follows plotted time series for 4 days of generated data, two weekend days followed by two work days. The data has been generated for 1000 persons, with the cold tap water temperature of 8.5 °C. The figures show flow and temperature (Figure 11); COD load (Figure 12); nutrient loads (Figure 13); COD concentration (Figure 14); and nutrient concentrations (Figure 15).

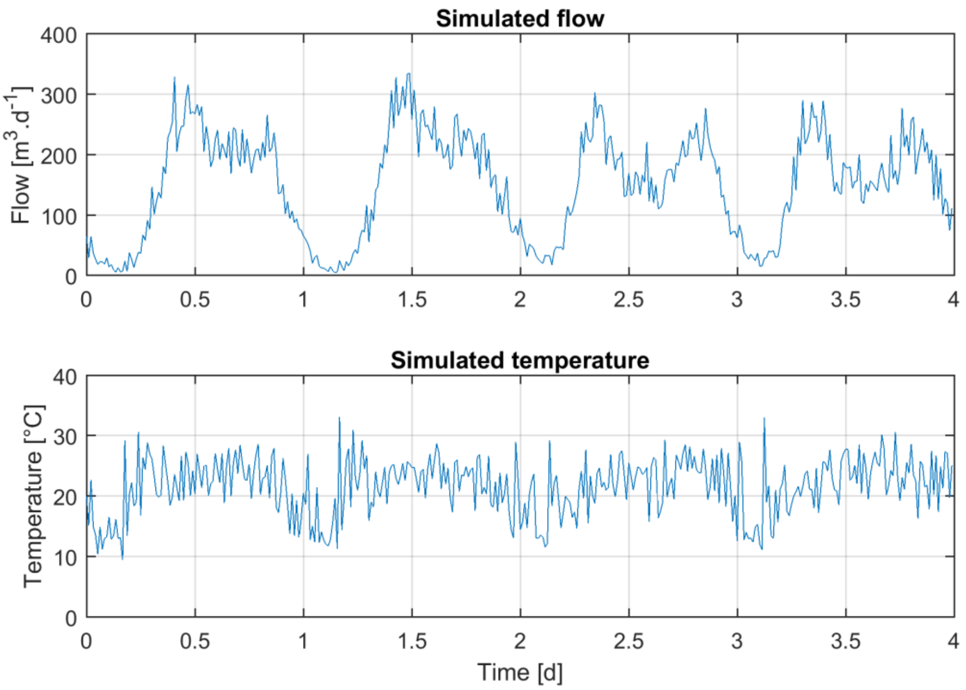

Figure 11. Simulated flow and temperature over two weekend days followed by two work days.

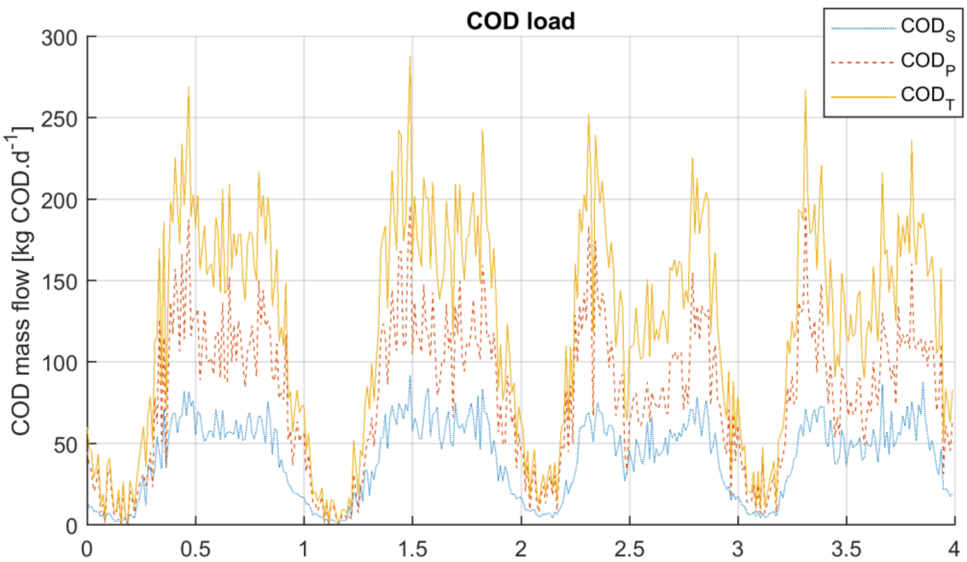

Figure 12. Simulated COD load over two weekend days followed by two work days, divided over total COD (COD_T), particulate COD (COD_P) and soluble COD (COD_S).

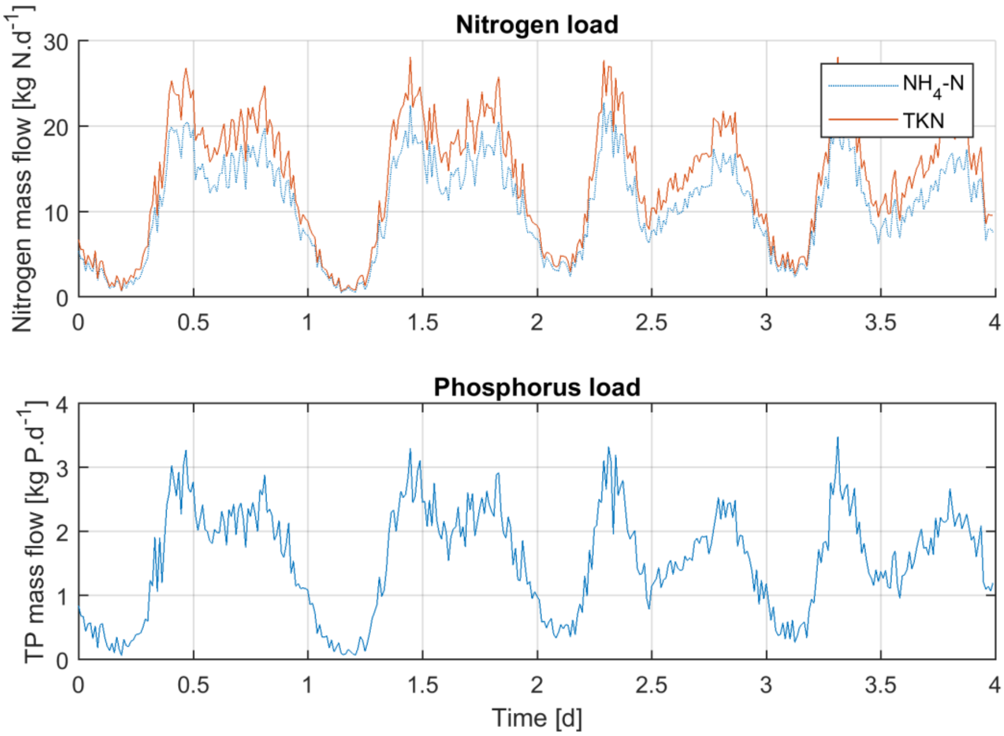

Figure 13. Simulated nutrient load over two weekend days followed by two work days, including nitrogen (upper: NH_4-N and TKN) and phosphorus (lower).

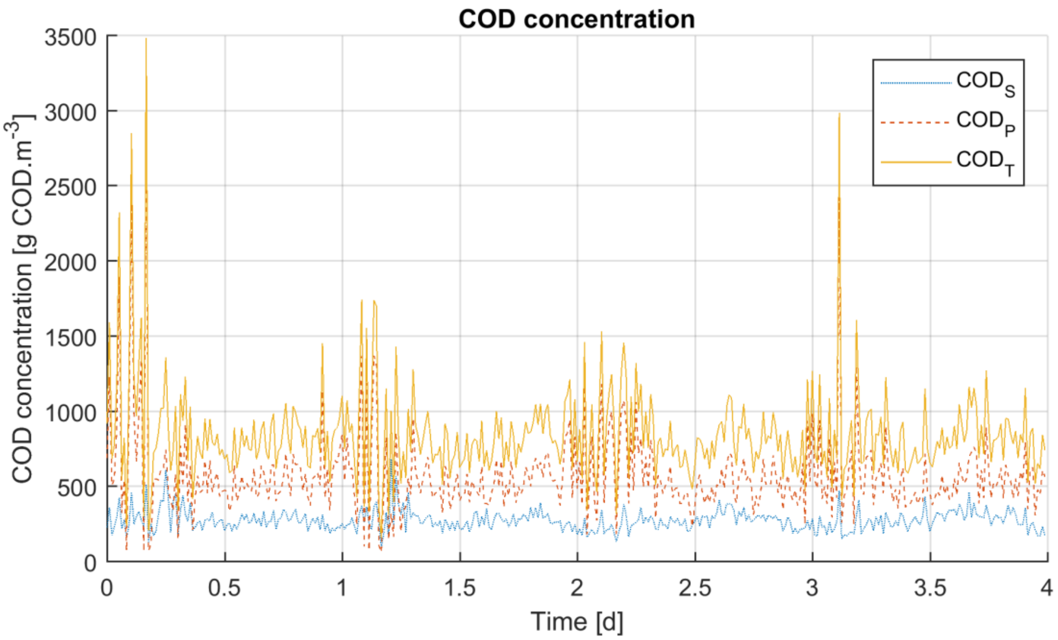

Figure 14. Simulated COD concentration over two weekend days followed by two work days, divided over total COD (COD_T), particulate COD (COD_P) and soluble COD (COD_S).

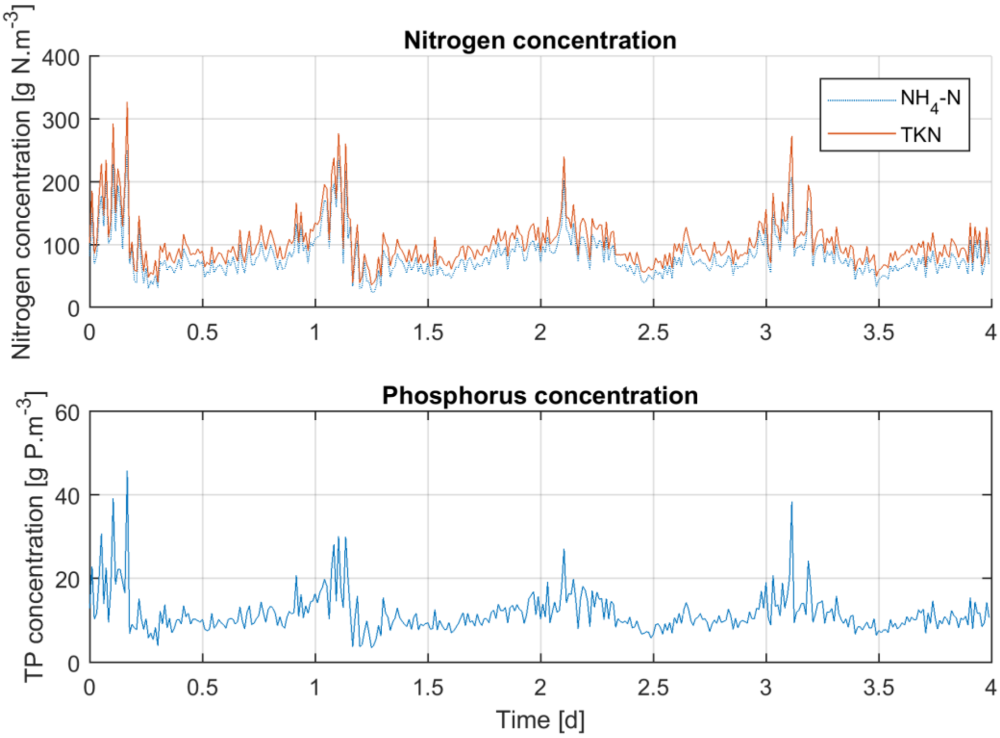

Figure 15. Simulated nutrient concentration over two weekend days followed by two work days, including nitrogen (upper: NH_4-N and TKN) and phosphorus (lower).

When compared to typical diurnal concentration and load profiles at the inlet of a wastewater treatment plant, some differences can be noticed. Examples of normalized (to the mean value) concentration profiles as well as flow at the inlet to Linköping WWTP is shown in Figure 16. As COD variations to the inlet has not been measured in Linköping, values for TOC (total organic carbon) are displayed instead as both are a measure of organic material in the wastewater and should show similar trends. Generally, the concentration profiles for the pollutants in Figure 16 follow the pattern of the flow, meaning that at low flow the corresponding concentration is low. The most obvious difference to the model results is that the concentration obtained by the model instead increases as the flow is low. This is possibly due to the fact that the flow from the model is undiluted, while the flow to WWTPs are diluted with infiltration water and stormwater. Infiltration rates to the sewer network varies slowly and can in this case be assumed constant during the course of a day. This cause a larger dilution of the flow as the wastewater flow is low during the night, thus causing the pollutant concentration to decrease. When the model is run with a constant base flow, the dilution causes the resulting concentration profiles to resemble the profiles measured at the WWTP (see Figure 17 for example of this, with 50% infiltration water added).

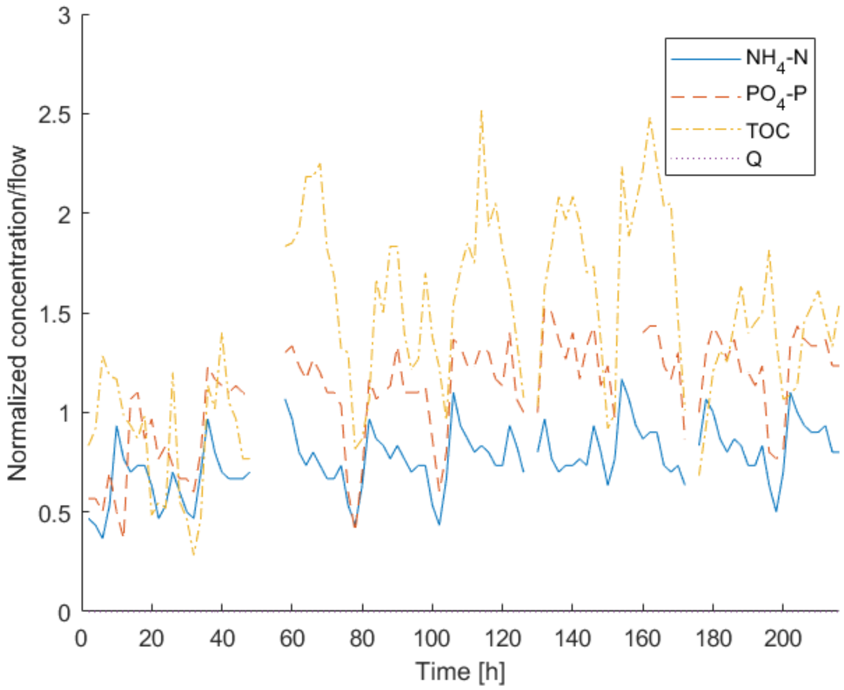

Figure 16. Normalized concentration profile for NH_4-N, PO_4-P and TOC as well as flow at the inlet of Linköping WWTP during measurements in 2006.

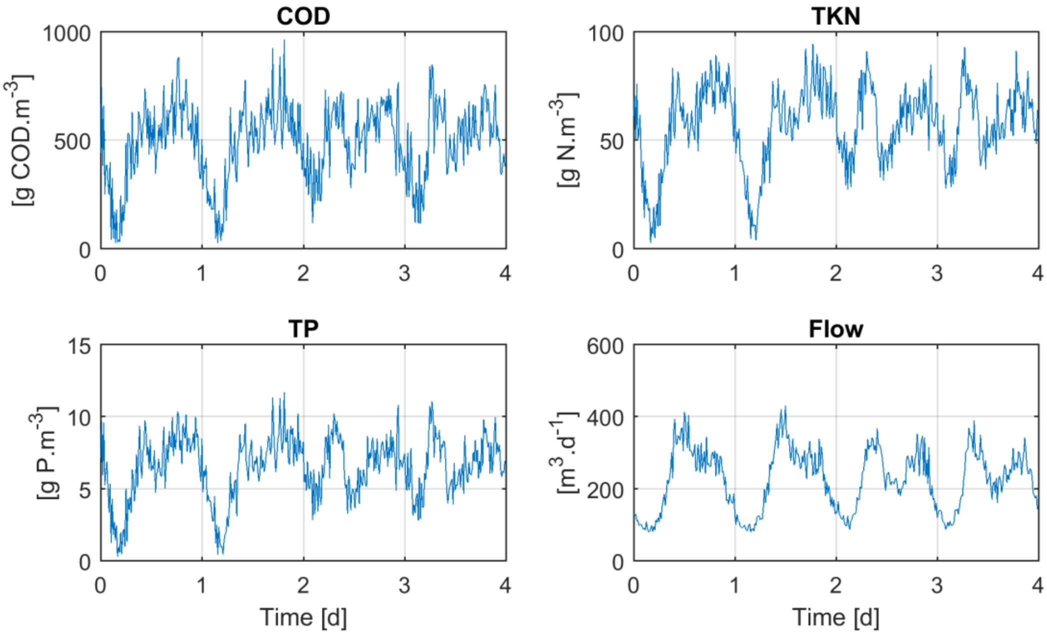

Figure 17. Pollutant concentration profiles for TKN, TP and COD_t as well as flow generated with the model with 50% infiltration water added for dilution effects. The results display simulation of two weekend days followed by two work days.

5 Implementation details

The model is implemented in Matlab (Matlab 2017b, Mathworks Inc., Natwich, MA, USA, 2017) as a function file and an initiation file for parameters and PDFs. The model is run by typing the function name, which produces an output vector with results. The results can be saved as a variable, and several different areas/buildings can therefore be simulated and added together. The following inputs are required to run the model:

1. The number of inhabitants to generate wastewater for;
2. The number of days to run the simulation;
3. A vector with the cold tap water temperature (one value per day) [°C];
4. The water temperature in the boiler [°C];
5. The starting day in the week (2-6 equals Monday-Friday, 7 equals Saturday and 1 Sunday;
6. The daily average water consumption per person [$L.person^{-1}.d^{-1}$];
7. A vector with the end use types to include in the simulation (displayed by the numbers 1-7). Each number and corresponding end use type is displayed in Table 9.

Table 9. Numbers representing each end use type included in the model.

1	2	3	4	5	6	7
Shower	Bathtub	WC_1	WC_2	Washing machine	Dishwasher	Taps

Since the vector with end use types must be included as input to the model, separation of certain wastewater streams can easily be simulated. An example can be to simulate shower use by itself and the rest of the end use types separately, then simulate heat recovery on the shower stream and finally merging the streams again.

The reference value for the generated water volume is the calibrated value from the case study in Linköping (184 $L.person^{-1}.d^{-1}$). To allow for flexibility to simulate other water consumption values, the difference between the reference value and the chosen water consumption is assumed to consist of equal parts shower and tap water. The model automatically recalculates the water use statistics (mean value of flow/duration) of shower and tap water use based on the assigned water consumption. If the water consumption that should be modelled deviates substantially from the reference value, the model should be used with caution and preferably be manually calibrated to the new conditions.

The model cycles through the days in order to generate values for each day of the week. The output from the model is a time series for the specified number of days of flow, temperature and pollutant load, with a resolution of 15 minutes (although the implementation allows the time step to be easily modified). The variables and their order in the output vector are displayed in Table 10.

Table 10. Output vector variables and order.

1	2	3	4	5	6	7	8	9
Time	COD_{sol}	COD_{part}	NH_4-N	TKN	TP	Flow	Temperature	Hot water flow
[d]	[kg $O_2.d^{-1}$]	[kg $O_2.d^{-1}$]	[kg $N.d^{-1}$]	[kg $N.d^{-1}$]	[kg $P.d^{-1}$]	[$m^3.d^{-1}$]	[°C]	[$m^3.d^{-1}$]

5.1 Example code

The code below shows an example of how the model is used to simulate the wastewater produced from 1 000 people for a period of 4 days. In the first example, all end use types are included, while in the second example only water from showers and washing machines is included. Note that for both examples, the water use should be entered as the total water use (regardless of which end use types are included).

5.1.1 Example 1 – all end use types

```
persons = 1000;

days = 4;

cw_temp(1:days) = 8.5;

hw_temp = 55;

water_use = 150;

end_use_vec = 1:7; %[1=show; 2=bath; 3=wc1; 4=wc2; 5=wash; 6=dish; 7=tap]

generated_ww =
ww_gen(persons,days,cw_temp,hw_temp,7,water_use,end_use_vec);
```

5.1.2 Example 2 – only shower and washing machine

```
persons = 1000;

days = 4;

cw_temp(1:days) = 8.5;

hw_temp = 55;

water_use = 150;

end_use_vec = [1 5]; %[1=show; 2=bath; 3=wc1; 4=wc2; 5=wash; 6=dish; 7=tap]

generated_ww =
ww_gen(persons,days,cw_temp,hw_temp,7,water_use,end_use_vec);
```

5.2 Model files

The model is comprised of three different .m-files:

- ww_gen.m: main script file;
- ww_gen_init.m: initialization file containing parameter values;
- pollutants_init: initialization file for specific pollutant loads.

Also included are .mat-files containing cumulative distribution functions for each end use type, derived from the PDFs. These are loaded by the ww_gen_init script to avoid the need to compute the PDFs each time.

The implemented model can be distributed upon request to christoffer.warff@ri.se.

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